Palo Alto Research Center

Device Independent Color Reproduction

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XEROX

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Device Independent Color Reproduction

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Abstract

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1 Introduction

Classic color reproduction systems tightly couple a specific input device (ie. scanner) to a specific output device (ie. printer). Color reproduction is then the process of transforming from the input colors to the output colors. In a device independent color reproduction system, the input and output transformations are defined relative to a standard representation for the color. This standard representation is usually based on some form of color measurement defined by CIE standard colorimetry.

The goal in color reproduction is to duplicate the appearance of the original on the target media. Colorimetry alone does not provide sufficient perceptual information to automate this process. That is, simply having a colorimetric definition for each color does not guarantee an acceptable reproduction. This statement has several implications. While current colorimetric standards are a significant improvement on the process-specific standards of the past, more information needs to be added to fully describe the desired appearance of a color. Furthermore, existing systems must have some way to compensate for this inherent limitation; either an interactive interface for making on-line adjustments, or a set of auxiliary transformations that compensate for appearance differences in different devices or classes of devices.

Colorimetric color reproduction has been explored in the prepress and computer graphics communities. In the prepress domain, it is often called "soft proofing" as the focus is to make a color monitor an acceptable proof for some printing process[35, 10, 11, 17]. In the computer graphics domain, the emphasis has been on reproduction of digital originals[39, 37, 32, 33, 42, 20], or desktop publishing style scan-modify-print systems[41, 1, 12]. This is still a very active field so these notes cannot provide a definitive solution or set of solutions. Furthermore, many solutions are being pursued in proprietary, industrial environments

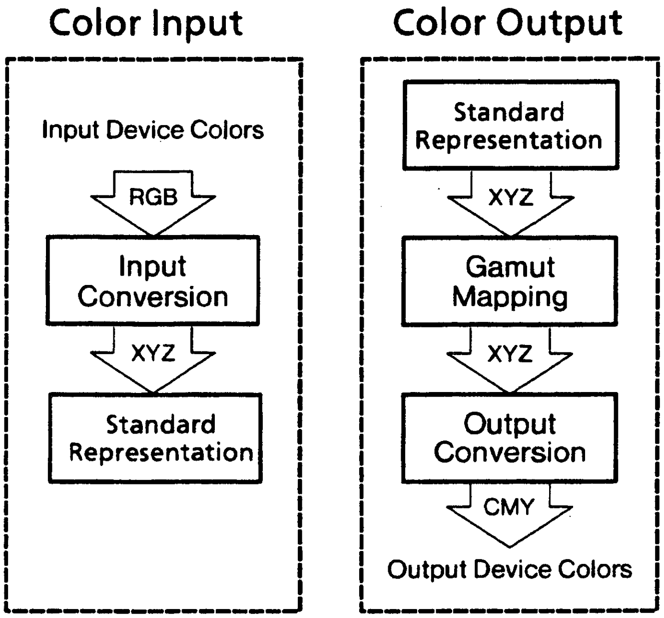

Figure 1: System diagram for input and output components of a colorimetric color reproduction system

rather than scientific ones, so a complete taxonomy is difficult to generate. However, some common problems and principles have been developed and will be presented here.

The structure of these notes is to describe a canonical colorimetric color reproduction system, then explore each of the pieces of the system in further depth. The intention is to motivate the particular emphasis used in describing the many disciplines that contribute to such a system.

2 System Overview

A canonical systems diagram for the input and output sections of a colorimetric color reproduction system is shown in figure 1. This diagram highlights the following system design problems. First, define a standard representation such as CIE tristimulus values or CIELAB or CIELUV. Then, develop a way to characterize each device with respect to this standard. This defines each device's *gamut*, or set of all possible colors. Finally, define a set of controls or transformations to compensate for gamut mismatches, differences in viewing conditions, and other appearance factors. This final step is typically performed only on output, for it is there that the gamut limitations are completely known.

The next sections provide more detail on each of these three system components. First is section on colorimetry and the CIE standards for specifying color. The following section will discuss digital color devices; both the native color representation (additive and subtractive color), and how to translate between this representation and the standard. Section 5 discusses gamut mapping, or the transformations needed to accommodate different device characteristics. Finally, some proposed standards for device independent color representation are reviewed in section 6.

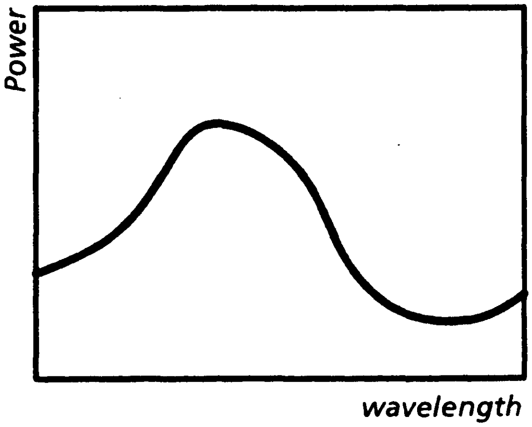

Figure 2: Typical spectra for a blue-green color.

3 Colorimetry

Human beings see color when light is reflected off a colored object, transmitted through a colored filter, or emitted directly as from the phosphors of a color monitor. Light is a physical quantity, but color depends on the interaction of light with the human visual system and is thus a psychophysical phenomenon. Research in vision has determined physical properties of light that are well-correlated with psychophysical properties of color. Colorimetry is the science of measuring color based on these physical properties, many of which have been standardized by the *Commission Internationale de l'Eclairage (CIE)*. Because these standards are well established in both science and industry, they provide a logical basis for specifying color in a digital system. There are several extensive reference works on color science and colorimetry[46, 3, 21]. These notes will provide only an overview of the important concepts and terminology.

3.1 Basic Principles of Color Measurement

Color can be defined as the response of an observer to a visual stimulus. This stimulus can be quantified as the spectrum of the light reaching the eye, that is, the energy of the light as a function of its wavelength. Figure 3.1 shows a typical color stimulus. The short wavelengths correspond to blue colors, the midrange to green and yellow, and the long wavelengths to red. The *spectral reflectance* of an object is the percentage of the light energy reflected at each wavelength and the color of an object is most precisely defined as its spectral reflectance. The *stimulus* that reaches the eye, however, is the product of the spectral reflectance and the spectrum of the light falling on the object, so the perceived color of an object can never be separated from its illumination.

The most basic aspect of a stimulus to quantify is brightness. Human beings see light when stimulated by electromagnetic radiation between roughly 350nm and 700nm but they do not see all these wavelengths equally well. The *luminous efficiency function* defines how efficiently the eye responds to light at each wavelength. Multiplying a stimulus by the luminance response curve and integrating produces a measure of how bright a color will appear called *luminance*.

The stimulus is a spectrum, but radically different spectra can appear the same color, an effect that is formally called *metamerism*. This principle makes it possible to use three phosphors on a color monitor or three inks in offset printing to produce a wide range of

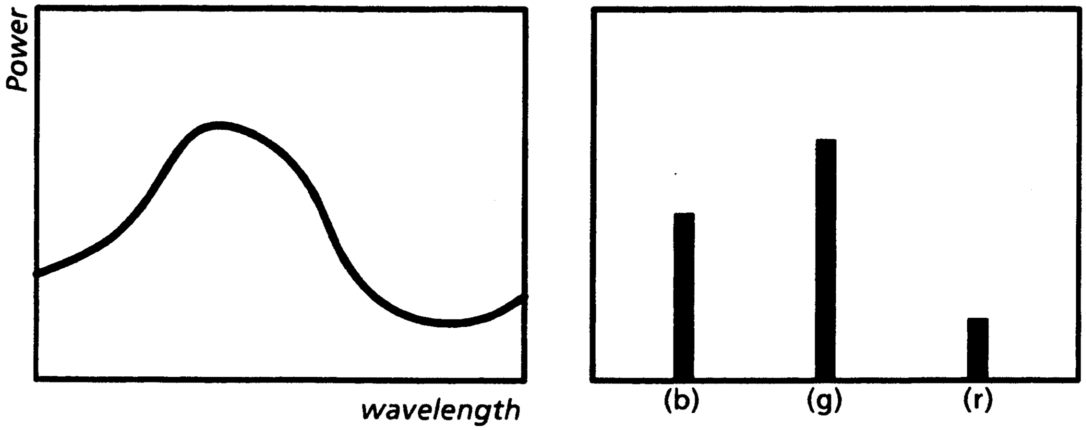

Figure 3: An example of metameric spectra. The one on the left is typical for a surface, the one on the right is three nearly monochromatic light sources.

colors. The number three in these systems is not coincidental; it is a directly related to the physiology of human vision. Figure 3 shows two different spectra that produce the same color. However, two objects that match under one set of lights will not necessarily match under any other set of lights unless the objects have the same spectral reflectance. A *metameric match* is one where the objects have different spectral reflectances but happen to match under a specific illuminant. All common color reproduction processes produce a metameric match to the original.

3.2 Tristimulus Values

While a color stimulus is a spectrum, the redundancy introduced by metamerism leads us to investigate whether color can be uniquely specified with less information. Imagine a color matching experiment where an observer has three primary lights, (typically red, green and blue), that can be adjusted to match a given color. Each color produced by the system can be defined entirely by the power of the primaries. These powers are called the *tristimulus values* for that set of primaries. It can be demonstrated that all colors can be matched (metamerically) by adding three independent light sources, if you allow the concept of negative light. In the mechanics of the color matching experiment, "negative light" means shining one of the primaries on the target color. In mathematical terms, it simply means allowing the tristimulus values to be negative numbers.

It has been empirically proven that different observers with normal color vision will produce the same tristimulus values for a given color, or, conversely, any stimulus that reduces to the same tristimulus values will look the same to any standard observer, assuming identical viewing conditions and observer adaption. By standardizing the primaries, therefore, we can define any colored light with just three numbers rather than an entire spectrum.

In the terminology of linear algebra, the primaries provide the basis for a three dimensional vector space. Each color is a vector in this space. If two stimuli are combined by addition (add the spectra wavelength by wavelength), the tristimulus values of the resulting color can be obtained by adding the tristimulus values of the stimuli. That is, the tristimulus values obtained by adding lights can be computed by adding tristimulus values as vectors. Similarly, scalar multiplication of the stimulus results in a scalar multiple of the tristimulus values. This formally defines the property of *additive mixture* and is an inherent property of the human visual system.

Given a set of tristimulus values defined relative to one basis (set of primaries), it is possible to transform them to another basis using a simple, linear transformation. Most standard primaries are not real light sources but have been designed to have specific properties such as making the tristimulus values positive for all visible color.

3.3 Color Matching Functions

The color matching experiment requires an observer to make judgements about which combination of primaries colors match a specific color. That is, to generate the tristimulus values for a color, an observer needs to make a match. It is much more useful to have a way to define the tristimulus values without using an observer each time.

The *color matching functions* are a way to capture the essential information about an observer that is needed to compute tristimulus values from a stimulus. Given a set of primaries, the color matching functions are defined by a color match to an equal energy white reference at regular intervals across the visible spectrum. This produces a set of three, empirical functions of wavelength that define the observer's response. The tristimulus values for a color stimulus can be computed by integrating the product of the stimulus with the color matching functions.

The color matching functions are valid only for a specific observer and a specific set of primaries. However, there is sufficient commonality among human observers that it is possible to create a standard observer. The standard primaries are arbitrary, though to actually perform the matching experiment they have to be real light sources

3.4 CIE Standards

The *Commission Internationale de l'Eclairage* is an international organization that has standardized a method for computing tristimulus values, denoted X, Y and Z, as a standard representation for colors. In 1931 the CIE standardized three primaries and a standard observer to produce color matching functions that are widely used by a variety of industries to quantify colors. These are specified as tables of data defining functions which are multiplied by the stimulus and integrated to produce the tristimulus values[46, pp 158–164]. These functions can be seen in figure 4.

Within a reasonable range, multiplying the spectral power distribution by a scalar does not change the perceived color (effectively, the ambient light changes in brightness). Projecting the tristimulus values on a plane of constant value factors out the lengths of the vectors while maintaining their relative positions. The resulting two-dimensional representation is known as the *chromaticity coordinates* of the color, and such a projection is called a *chromaticity diagram.* The commonly used chromaticity coordinates are x and y, where $x = X/(X + Y + Z)$ and $y = Y/(X + Y + Z)$.

The familiar CIE *chromaticity diagram* shown in figure 5 is a plot of x vs. y. Included on this plot is a horseshoe-shaped curve called the *spectrum locus* that is defined by the chromaticity coordinates of the spectral (single frequency) colors. The *purple line* is the line connecting the blue with the red end of the spectrum locus. All visible colors lie inside the region bounded by the spectrum locus and the purple line. The black-body radiation curve describes the chromaticity coordinates for black body radiators of different color temperatures. All colors described as "white" lie near the black-body curve. The colors on the spectrum locus represent pure, saturated colors.

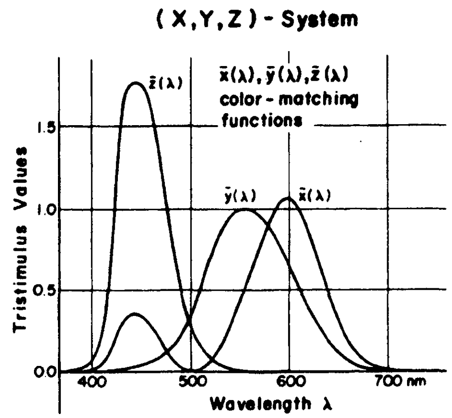

Figure 4: Color matching functions for the CIE 1931 standard colorimetric observer[46, p. 137].

The property of additive mixture can be applied to chromaticity coordinates. If two colors are represented by points on a chromaticity diagram, any color that is a mixture of the two lies on the line connecting them, though precise position on the line must be derived from the tristimulus values rather than the chromaticity coordinates. This provides a way to visualize the appearance of colors on the chromaticity diagram with respect to a reference white. Draw a line from the white through the color to the spectrum locus. Colors on this line will be roughly the same hue and increasing in saturation as they approach the spectrum locus. The terms *dominant wavelength* and *purity* are used in this context.

3.5 Color Difference Formulas

The Euclidean distance between two colors defined as tristimulus values is not a good measure of how similar the colors appear. That is, the minimum perceptible difference between colors corresponds to a different distance in different parts of the color space. Several attempts have been made to derive perceptually uniform color spaces from the tristimulus values. In 1976, the CIE recommended the use of two approximately uniform color spaces, CIELAB and CIELUV.

These two systems were derived from ones that already existed in different industries at the time the CIE addressed the problem of recommending a uniform color space. The CIE recommendations recognize both spaces as being better than tristimulus values for comparing colors, although neither was found to be truly uniform nor significantly better than the other. The intent of the standard is to formally define the *just noticeable difference (JND)* between two colored samples. The samples must be viewed under identical conditions.

The systems are similar in many respects. Both of the systems use a metric for lightness called L^* (L-star), which is proportional to the cube-root of the luminance.

$$\begin{aligned} L^* &= 116\left(\frac{Y}{Y_n}\right)^{1/3} - 16, \quad \frac{Y}{Y_n} \geq 0.01 \\ L^* &= 903.3\frac{Y}{Y_n}, \qquad\qquad \frac{Y}{Y_n} < 0.01 \end{aligned}$$

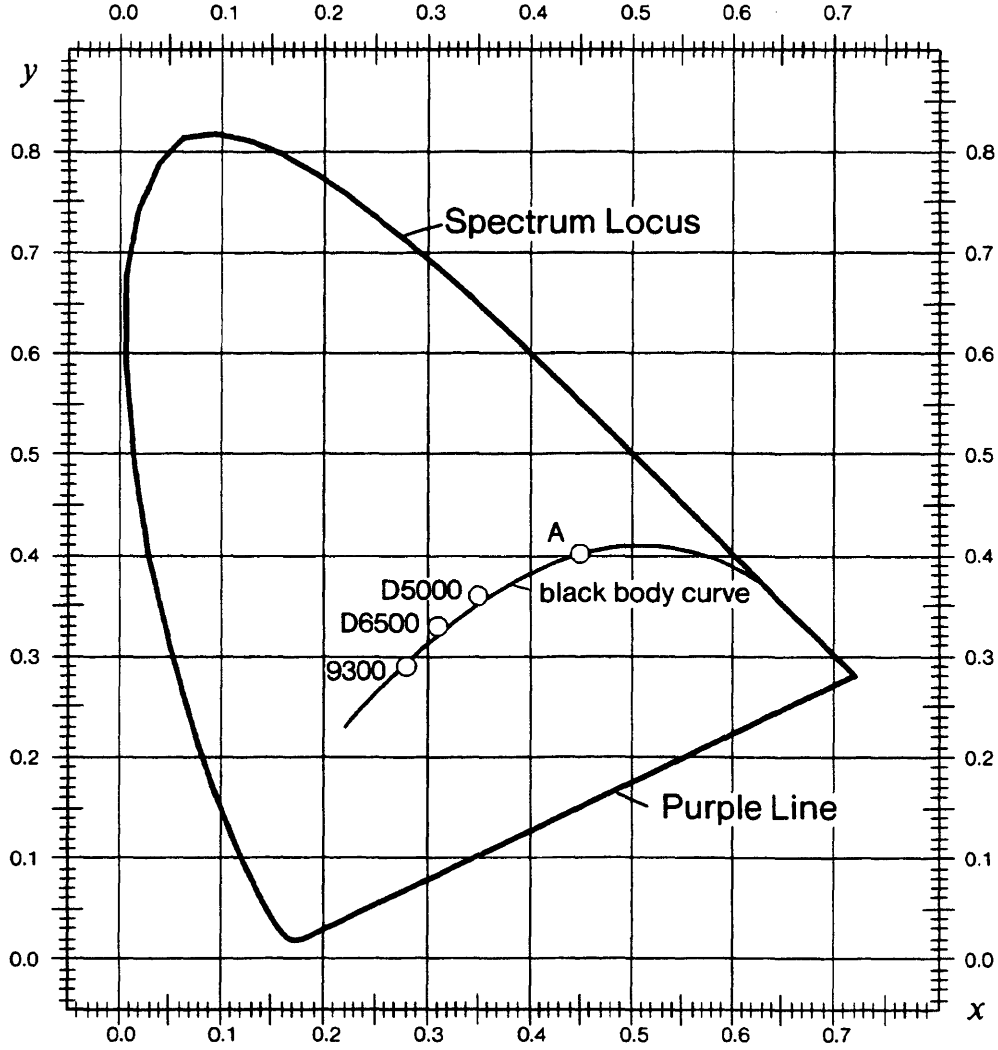

Figure 5: The CIE chromaticity diagram showing the spectrum locus, purple line, black-body curve and the location of three standard illuminants: D5000, D6500 and A. Illuminant A corresponds to incandescent light. A typical computer graphics monitor white point (color temperature 9300) is also shown.

where Y_n is the luminance of the reference white. Note that a relative luminance of less than 0.01 is very dark. The quantity L^* is considered to be good approximation to perceptual brightness.

L^* is defined with respect to a reference white and normalized so it always falls in the range of 0 (black) to 100 (white). The other two axes, a^* and b^* for CIELAB or u^* and v^* for CIELUV, define the colorfulness of a color.

CIELUV is defined as:

$$\begin{aligned} u^* &= 13L^*(u' - u'_n) \\ v^* &= 13L^*(v' - v'_n) \end{aligned}$$

where (u'_n, v'_n) are the metric chromaticity coordinates of the reference white.

CIELAB is defined as:

$$\begin{aligned} a^* &= 500\left[\left(\frac{X}{X_n}\right)^{1/3} - \left(\frac{Y}{Y_n}\right)^{1/3}\right] \\ b^* &= 200\left[\left(\frac{Y}{Y_n}\right)^{1/3} - \left(\frac{Z}{Z_n}\right)^{1/3}\right] \end{aligned}$$

where X_n, Y_n, Z_n are the tristimulus values of the reference white and none of the ratios are less than 0.01. There are modified versions of these formulae for very dark colors[46, p.167] but these are rarely needed in practice.

A single JND is a Euclidean distance of 1 in either system. Maintaining any color reproduction process to a JND of 10 or less is quite difficult. Single JND values are more commonly applied to paints, inks and other colorants.

One convenient way of visualizing these systems is in cylindrical coordinates around the L^* axis. *Hue angle* is the angle with respect to the positive a^* or u^*, and *chroma* is the distance radially from the origin[46, pp. 168–169].

While used in an identical manner, the shapes of these two systems are quite different, especially for saturated colors, as shown in figure 6. This figure shows the spectrum locus and the region of the color space for which the claim of uniformity has been evaluated. Most color monitor gamuts contain colors that lie outside of this region.

3.6 Instrumentation

Luminance, reflectance and the CIE tristimulus values can be measured with a *spectroradiometer* or *spectrophotometer* that samples the stimulus at a number of different wavelengths, multiplies it by the color matching functions, then sums the results to perform the integration and produce X, Y, Z. Such a device generates complete spectral information for the stimulus. A spectroradiometer can function as a radiometer, that is, it can measure absolute light energy. It can therefore be used to measure objects lit by arbitrary light sources. A spectrophotometer contains an internal light source and has detectors matched to that specific source. A *colorimeter* contains three filters whose transmittances are close to the color matching functions. Measuring the total light energy through each filter defines the tristimulus values. A colorimeter is not as accurate an instrument as a spectroradiometer, and cannot be used to measure complete spectral information. However, the results obtained from a colorimeter are usually precise and repeatable, so a colorimeter can be used to check variance from a standard.

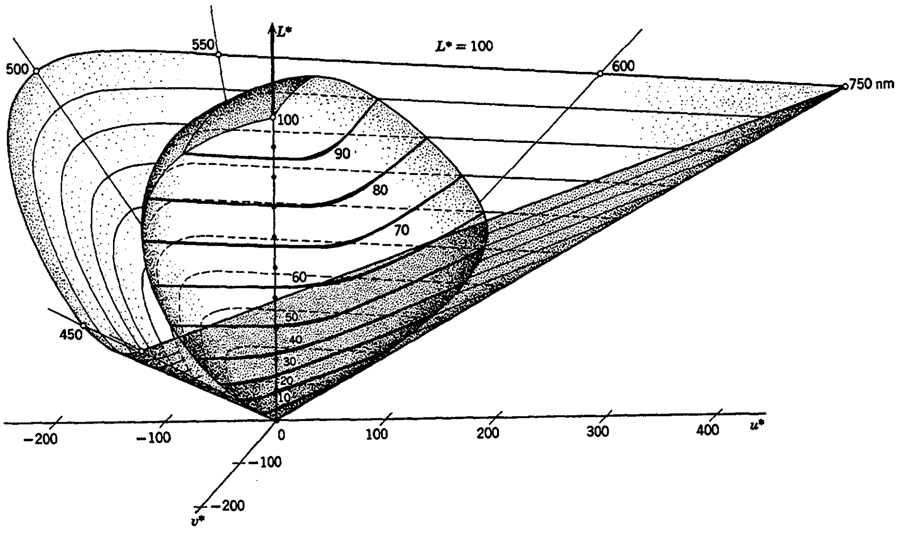

Fig. 1(3.3.9). Sketch of CIE 1976 ($L^*u^*v^*$) color space with outer boundary generated by optimal color stimuli with respect to CIE standard illuminant D_{65} and the CIE 1964 supplementary standard observer. The colors of all object-color stimuli fall within this boundary. This is also the gamut within which the CIE 1976 color-difference formula $\Delta E(L^*u^*v^*)$ is intended to be valid. Note that the spectrum locus of monochromatic stimuli is generally well outside the boundary of object-color stimuli (from Judd and Wyszecki, 1975).

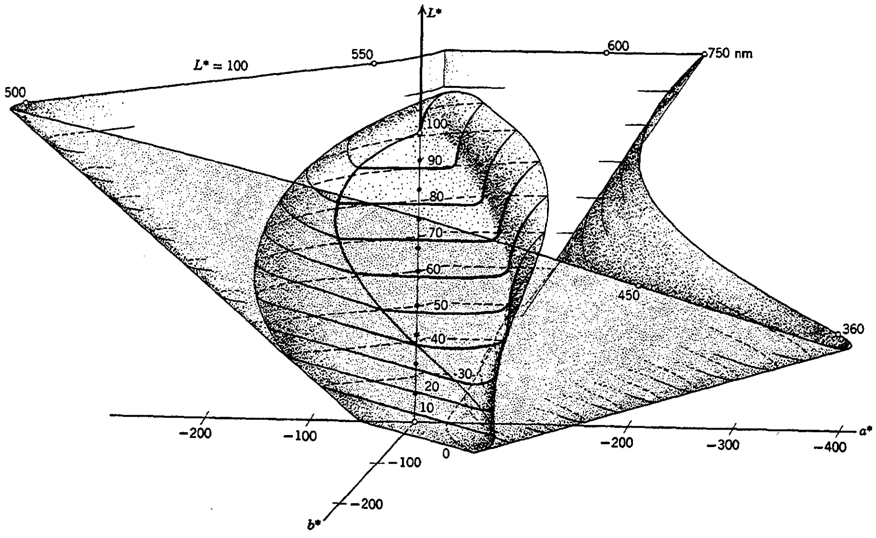

Fig. 2(3.3.9). Sketch of CIE 1976 ($L^*a^*b^*$) color space with outer boundary generated by optimal color stimuli with respect to CIE standard illuminant D_{65} and the CIE 1964 supplementary standard observer. The colors of all object-color stimuli fall within this boundary. This is also the gamut within which the CIE 1976 color-difference formula $\Delta E(L^*a^*b^*)$ is intended to be valid. Note that the spectrum locus of the monochromatic stimuli is generally well outside the boundary of object-color stimuli (from Judd and Wyszecki, 1975).

Figure 6: Sketch of the CIELAB and CIELUV color spaces[46, pp. 166–167]

4 Device Calibration and Characterization

The common digital color output devices are film recorders, printers (in a variety of technologies), video recorders and color monitors. These devices converts digital data to colored pixels which are then displayed, printed or recorded. A color scanner converts an image (print, film, or video) to digital form. The color information passed through the digital interface is device specific. The form depends on the technology used to produce (or generate) the color. In these notes, *device characterization* is the process of measuring the colors produced by a specific piece of equipment and developing a transformation between the device specific representation and the standard, colorimetric representation. *Calibration* is the process of adjusting the equipment to comply with a device level specification. This guarantees that the equipment is operating correctly and may simplify the characterization by forcing linearity, uniformity, etc.

In a laboratory situation, calibration and characterization are often tightly coupled. In a distributed environment like desktop publishing, however, calibration is performed by the manufacture and by repair personal. Calibration occurs infrequently, when the equipment is installed or repaired. Characterization is performed by the user as part of an initialization sequence or possibly by a systems administrator. The equipment is measured as it is really used. Ideally, characterization would occur frequently, perhaps once a day or before any critical color evaluation was performed.

This model has several advantages. It allows the user to make adjustments such as increasing the contrast on a monitor viewed in a well lit office. It accommodates aging and other sources of variability in equipment. It does demand a characterization procedure that is fast, easy to use and as automated as possible. However, given such a procedure frequently used, the reliability of the characterization should be high.

Characterization can be performed either by modeling the specific process used to produce color on a particular device, by sampling the local color space densely enough to build an accurate set of look up tables, or by a combination of the two methods. The next sections of these notes will discuss the device specific representation of color used in typical digital color media, followed by discussion of the different characterization methods.

4.1 Additive and Subtractive Color Reproduction

Color reproduction methods are classified as either additive or subtractive. In either form, the original image is separated into its red, green and blue color separations. The choice of red, green and blue gives full coverage to the spectrum (figure 7). Each separation is reproduced independently. The principle of additive mixture guarantees that combining the three reproductions will reproduce the appearance of the original image (assuming identical viewing conditions and viewer adaptation). In an additive reproduction system, an image is produced using three light sources, one per separation. Adding the output of these sources (shining them all on the same surface as in a video projector, or combining them spatially as in the phosphor dots of a monitor) reproduces the image, as shown in figure 8.

A subtractive reproduction system uses a single, white light source. By passing the light through a series of filters (inks or dyes), controlled amounts of red, green and blue light are subtracted from the white light. That is, all the unwanted light is removed, leaving only the components specified by the color separations. Cyan, magenta and yellow are called the subtractive primaries because each modulates one component of the red, green, blue color separations. A cyan filter attenuates red light and passes all other colors. Similarly,

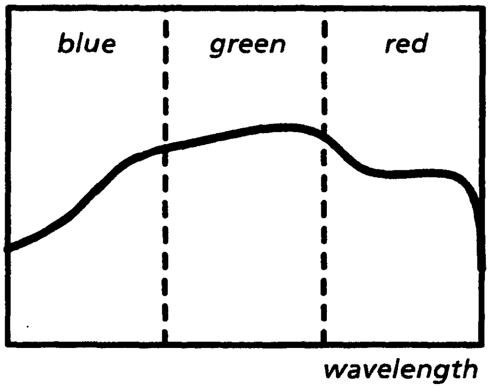

Figure 7: The visible spectrum divided into its "red", "green" and "blue" components.

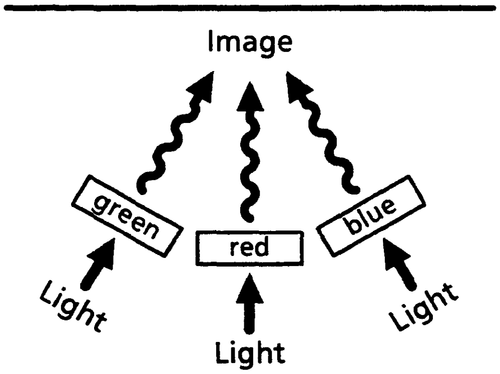

Figure 8: Diagram of an additive color reproduction system such as is used in a video projector.

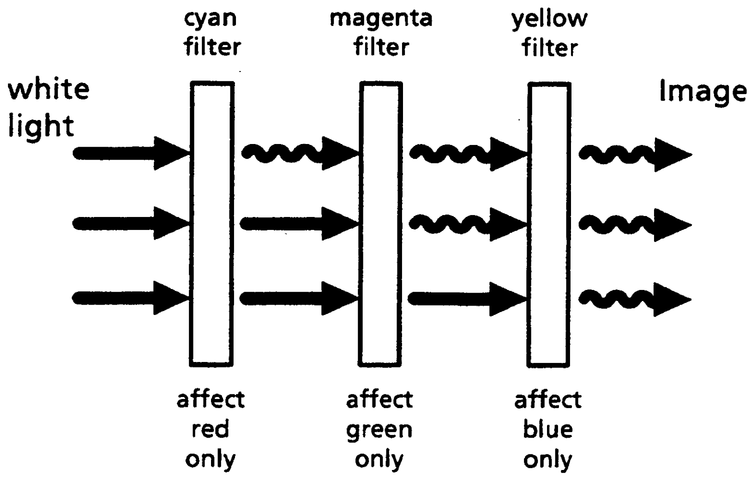

Figure 9: A subtractive color system such as is used for projective film. For printed color, the light passes through the filters (inks) and reflects off of the white paper.

a magenta filter attenuates green light and a yellow filter attenuates blue light. Figure 9 illustrates subtractive color reproduction.

Until the advent of color television, additive color reproduction was fairly uncommon because three light sources are inefficient (produces a dim image) and difficult to align. Video projectors, for example, demonstrate these problems. Color monitors, however produce well-aligned, vivid color images. The common subtractive reproduction systems are photography and printing. While efficient and well aligned, it is more difficult to predict and control the color in a subtractive color system because dyes and inks do not act as ideal filters for the white light source

4.2 Additive Color Output Devices: Monitors and Video Recorders

4.2.1 Monitors

The signal input to a digital color monitor is voltage levels to drive the electron guns that stimulate the phosphors on face of the picture tube. The three phosphors (red, green, blue) are deposited in as a pattern of dots or stripes and masked so each gun stimulates only one color. The color at each pixel is defined by summing the contributions from each of the phosphor dots forming that pixel. The definition of "red", "green" and "blue" is defined by the composition of the phosphors. These vary across different models of monitors. White is defined by the balance of the three primaries at maximum voltage. White varies widely across monitors, with a typical range of color temperatures between 6500K to 9300K. While some graphic arts monitors are set to a color temperature of 5000K, this noticeably limits the overall brightness.

There is a well defined relationship between the voltage applied to the electron gun and the intensity of the emitted light: $I = V^\gamma$, where gamma typically lies between 1 and 3. Gamma correction is the process of mapping the input voltages so that they correspond to linear intensity rather than linear voltage. While common practice is to assume that linear intensity can be achieved with a constant and uniform gamma for the three guns, a more complex mapping may be required.[6, 30, 24].

A monitor must be continuously updated so the voltage levels for the red, green and blue (RGB) component of each pixel are stored in a *frame buffer*, typically at 8 bits (256 levels) per color. The frame buffer can either hold the full RGB representation, or it can store an index into a color lookup table (LUT) or *colormap*. This table maps an index (usually 8 bits) into a full color value. Some full color systems include a set of three lookup tables, one for each color, that can be used for gamma correction or other linearization functions.

4.2.2 Video Recorders

In North America, a video recorder encodes RGB video signals as NTSC standard video[13, ch. 22, pp. 439–476]. The NTSC color space (IYQ) is defined as a linear transformation of a specific RGB color space, though common practice is to apply the transformation to any RGB signal. The I,Y and Q signals are then quantized and encoded. Experience indicates that the color shifts caused by the encoding are severe. Furthermore, inter-pixel color effects are introduced that are difficult to model, that is, the color of a pixel is dependent on the color of adjacent pixels. Video is displayed on a color monitor identical in principle to the ones used on computer displays, though they are typically lower in resolution and brighter.

4.2.3 Calibration and Characterization

A digitally controlled color monitor can be calibrated to be an ideal additive color device[6, 7]. The phosphors function as basis for a linear color space as did the primaries in the color matching experiment. This means that the tristimulus values can be computed using a linear transformation defined by the phosphor tristimulus values as shown below:

$$(X,Y,Z) = (R,G,B)\begin{pmatrix} X_R & Y_R & Z_R \\ X_G & Y_G & Z_G \\ X_B & Y_B & Z_B \end{pmatrix}$$

This model assumes that no ambient light is reflecting off the face of the monitor.

It is important to understand that careful calibration is required to make this model accurate. Fortunately, manufacturers such as Barco and Radius are producing "self-calibrating" monitors. These systems include instrumentation for measuring intensity and a microprocessor for operating a calibration sequence, all under digital control.

It is impossible to discuss characterizing a video recorder independent of the player and monitor used to display the resulting tape. Even assuming a fixed combination of recorder, player and monitor, the author knows of no model that includes all these components. There are broadcast standards[36] for calibrating each of these components. Given a fixed system, it may be possible to develop a characterization based on sampling.

4.3 Subtractive Color Output Devices: Film Recorders and Printers

4.3.1 Film Recorders

A digital film recorder exposes color film through red, green and blue filters. The exposure system can be a point light source which (slowly) scans the film, or it can be a monochrome monitor. Monitor exposure systems can either expose one scanline at a time or expose the

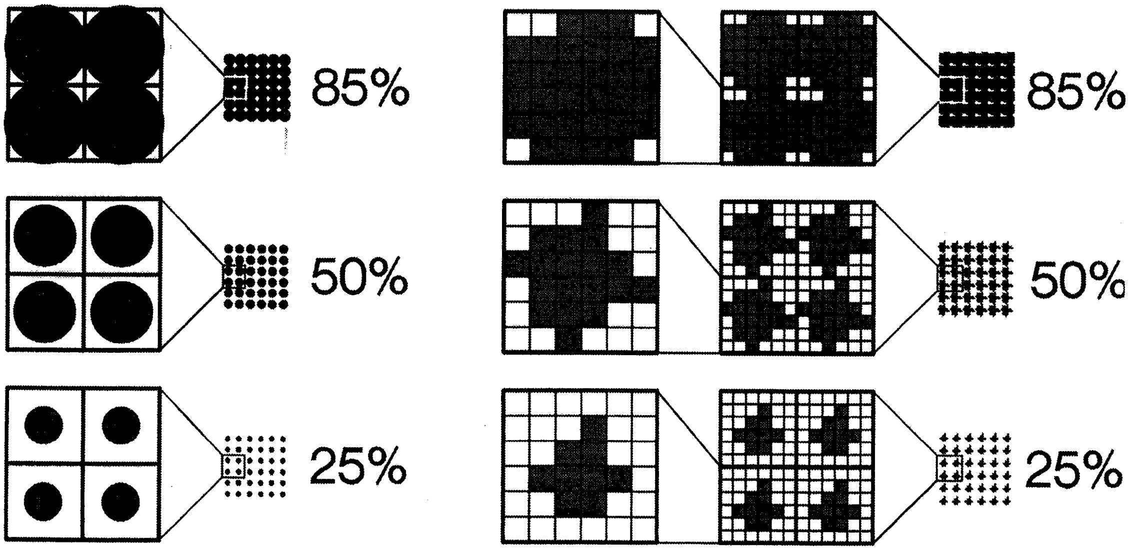

Figure 10: (a) Idealized halftone patterns for 25%, 50% and 85% dot area. (b) Digitally produced halftone patterns for 25%, 50% and 85% dot area using Holladay's algorithm[19]. Original image by Chuck Haines, Xerox Corp.

entire frame at once. The digital signal to the recorder are red, green and blue values. These can either be the video signals to the recorders internal monitor, the voltage values for the electron guns that drive the monitors, or (on some high performance systems) film density values. The mechanism for reproducing the image is subtractive (dye layers in color film), and the interface to the film recorder is the three color separations, expressed as RGB pixels. The color of the output is defined by the input values, the characteristics of the film and its development, and by the color of the light source used to view it.

4.3.2 Printers

A printer deposits some form of ink on paper. Most printers are bi-level, that is, ink is either present at a point on the paper or it is not. The illusion of intensity levels must be achieved using patterns of dots called *halftones.* Originally, halftones were produced by photographing the original through a screen called a *halftone screen.* Nowadays, halftone patterns are built up out of many tiny pixels on a high resolution film printer, as shown in figure 10. A few printing processes are capable of generating intensity levels without halftoning. Some deposit different densities of ink. Some create pixels of different sizes in a pattern similar to halftoning.

Many different technologies are used in digital printing. Impact printers work like a typewriter; ink from a ribbon is transferred by pressing it against the paper. Ink jet printers drop or spray liquid ink on the paper. Electrostatic printing puts charge on special paper and runs it through a charged liquid ink. Xerography also uses charge to define the image (using a transfer surface rather than special paper), but typically uses a dry ink (toner) that is fused to the surface of the paper. Thermal transfer printers melt wax from a mylar ribbon onto the surface of a paper.

Thermal dye diffusion printers heat the dye embedded in a mylar ribbon, sublimating it onto the paper surface at densities proportional to the energy applied to the print head, producing multiple gray levels per color. Other technologies that produce multiple color levels per pixel are microencapsulation, dry silver color and multi-drop inkjet. Microencapsulation technology combines three dyes in the ribbon, each sensitive to red, green or blue light. The exposed dye is pressed on the paper. Dry silver color uses photosensitive paper and heat development. In these two cases, the final color is proportional to the intensity of the exposing light. Multi-drop inkjet printers can modulate the number of ink droplets deposited per pixel. The more ink, the darker the color.

Modern graphic arts production printing is almost always either offset lithography or gravure. Offset is a halftoned process; the plates are made by exposing them through photographically produced halftoned separations. Gravure is not halftoned; the cylindrical plates are marked with a pattern of holes drilled to different depths. The deeper the hole, the more ink deposited at that point. Both of these systems now have digital interfaces. For offset, the interface is at the digital printer that creates the halftoned film separations. For gravure, the drilling machine for the cylinders is digitally controlled.

The interface to a printing system describes the amount of ink to deposit at each pixel position. Either three or four colors of ink are typically used: cyan, magenta, yellow and (optionally) black. The output color is ultimately defined by the color of the ink, paper and light source. However, assuming "color" to includes intensity variations, the halftone pattern plays a significant role in defining the output color. Most discussions on color printing include the art and science of halftoning[43, 44].

4.3.3 Printing black, Gray balancing and GCR

The subtractive primaries used in a printing system are cyan, magenta and yellow; these three colors are adequate to reproduce a color image. In printing systems, the maximum density that can be achieved by overprinting three printing inks can be significantly improved by overprinting black. This improves the contrast of the reproduction.

Ideally, the inks representing the three subtractive primaries would filter three independent sections of the spectrum, as shown by the dotted lines in figure 11. Such inks are often called *block inks.* Real ink transmittances are shown in the solid lines in the same figure. There is overlap in the portions of the spectrum modulated by the different inks, especially between cyan and magenta. This lack of independence means that the gray values produced by combining equal portions of the inks are tinted. Compensating for this is called *gray balancing.*

The black separation can be used to help compensate for the impurity of color printing inks. Any color that combines all three subtractive primaries can be separated into its gray component (MIN[C,M,Y]) and its color. Some or all of the gray component can be replaced with black ink, a process called gray component replacement (GCR). Much has been written about the best way to perform GCR[16, 43]. The issues are overall density (a four color black is darker than a single color black), alignment at the boundary of neutral (all black ink) and tinted regions of the image, and economy (colored inks are more expensive than black ink). Any algorithm for defining the proportion of the four inks must be supported by experimental data. The density obtained by overprinting inks cannot be easily predict from the individual ink densities, a problem referred to as *additivity failure*[43, pp 216-232].

A diagram showing two examples of the relative proportions of cyan, magenta, yellow and black typically used to produce a neutral gray on an offset press is shown in figure 12. Figure 12 (a) shows a skeleton black, that is, black added only to increase contrast. Figure 12 (b) shows a black combined with GCR.

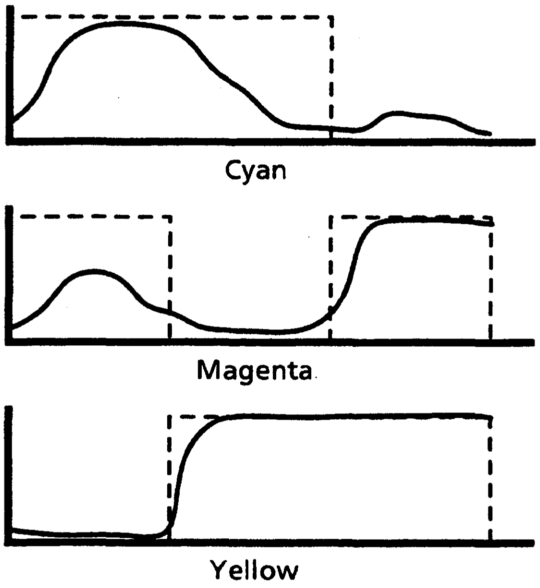

Figure 11: Ideal vs. real ink transmittances. The dotted lines are ideal, non-overlapping inks. The solid lines are actual ink transmittances.

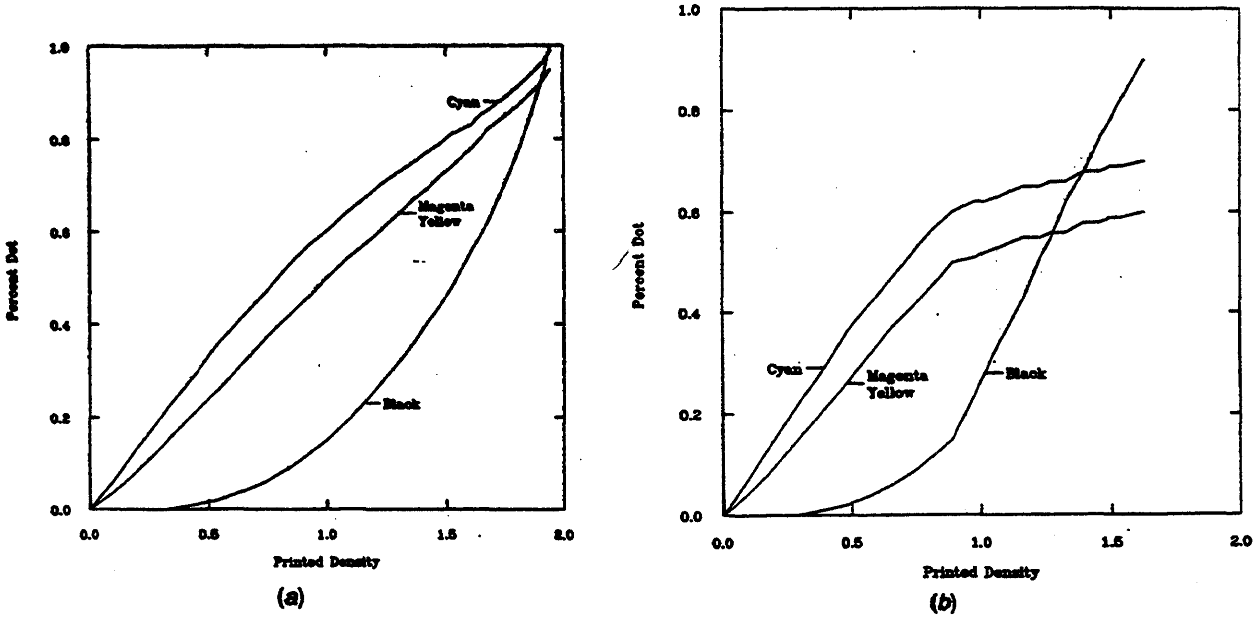

Figure 3. Plots data on ink as a function of printed density of the reproduction for conventional neutral; data kindly supplied by Graphic Arts Technical Foundation. (*a*) 400% UCR (essentially no limit on total ink coverage) with a modest amount of GCR. (*b*) 280% UCR.

Figure 12: Plots showing the balance of process color inks for (a) a skeleton black and (b) 280% recommended UCR[11, p. 55].

4.3.4 Calibration and Characterization

Subtractive processes are measured in terms of density. Qualitatively, density is a measure of opacity or darkness. An inexpensive tool called a *densitometer* can be used to measure density. However, care must be taken to understand precisely which form of density is being measured[13, 46, 43].

The simplest form of density is *optical density*, defined as:

$$D(\lambda) = -\log_{10}\tau(\lambda) = \log_{10}\frac{1}{\tau(\lambda)}$$

Density provides a convenient way to calculate the effective transmittance of combined filters because a product of transmittances can be expressed as a sum of densities.

Subtractive processes must be calibrated relative to a give light source. For prints, this is the ambient light in the viewing environment. For quality reproduction, a standard viewing booth is recommended. This controls not only the light but the color of the background. For transparency film, light is provided by a light table or by the bulb in the film projector. Common light sources vary significantly, from the reddish-yellow color of incandescent bulbs to the blue-white of daylight and fluorescent sources. This variation will make a significant difference in the perceived color.

For a given set of inks and paper, calibrating a printing engine means adjusting the ink densities and the press alignment. For a halftoned printer, the density and viscosity of the ink affect the size of the halftone dots, a process called *dot gain* in conventional printing[43, 4]. All of these properties affect the final color. Traditionally, a printer is calibrated if a neutral gray test wedge can be printed that is gray and has the predicted density at each point.

Similarly for a given film and film processing procedure, a film recorder should be adjusted until equal amounts of red, green and blue produce a neutral gray, and the output density is a predictable function of the input values[5]. Most film recorders have internal controls for these functions.

A characterization for a subtractive system must assume a fixed light source, media (paper, ink, film) and a calibrated device. In offset printing, there is a model for the interaction of ink, paper and light that can be used to predict tristimulus values from halftoned dot area called the Neugebauer equations[26, 43, pp. 260-266]. These equations are derived from statistical models which define the percentage of the paper covered by ink of different colors. Several modifications of the basic equations have been required as these equations have been applied[34, 43, 11]. In theory, these same equations can be applied to any printer which produces halftone patterns similar to the ones used in offset printing.

4.4 Color Scanners

4.4.1 Operation

A color scanner views an original image through red, green and blue filters. The intensity of the light seen through each filter is converted to digital values. The scanning system can image a single point at a time, a scanline at a time or the whole image at once (as in a video camera). The actual color corresponding to the output values depends on the filters and the light source. An ideal scanner would use filters that correspond to human color matching functions, like a colorimeter. This would guarantee that colors which were a metameric match would produce the same pixel values and would produce tristimulus values directly. In practice, this is difficult to achieve[10] so few scanners are colorimetric

In traditional graphic arts systems, the input scanner not only generates the red, green, blue separations for the image, but also performs the conversion to cyan, magenta, yellow and black output values. The scanner controls are complex and a skilled operator is needed to perform the different color manipulations. Digital scanners for computer applications are much more limited and often produce results that severely degrade the appearance of an image.

4.4.2 Calibration and Characterization

Calibrating a scanner involves evaluating uniformity across the page area, and determining the range of pixel values produced. Scanning a test target of uniform color will define the uniformity, and scanning a black and a white test target could produce the maximum range of pixel values.

Most scanners contain their own light source and have detectors with sensitivities matched to this known source. The exception is video cameras, which operate under the ambient illumination. Given the spectrum of the light, the response of the detectors and the transmittance spectra of the filters, it is possible to compute the surface reflectance for each color. From this, the tristimulus values for a standard light source can be computed. Another approach is to measure a sample chart of known colors and build a table that describes the correspondence between the output pixels and the input colors. Note, however, that as the scanner is not colorimetric, different media with the same tristimulus values can give different pixel values, so the table is valid only for one particular medium (for example, a specific photographic paper).

4.5 Characterization Procedures

Characterization maps between a standard, usually based on CIE tristimulus values, and device coordinates. For each new characterization, it is necessary to first determine the stability of the device and appropriate accuracy for the characterization. Each characterization, whether model based or strictly sampled, involves some form of data collection. The measurement methods should be standardized for precision and recorded in a digital form that can be fed directly to the characterization implementation to avoid transcription errors. The characterization procedure should also include a simple and fast way to test whether the accuracy is within acceptable limits.

4.5.1 Stability and Uniformity

Stability is computed by measuring several sets of test samples produced over an some period of time. The appropriate period of time depends on the application and the device (throughout the day for some systems, over several weeks for others). This will measure the stability of the color device plus the stability of the measurement system. To determine the stability of the measurement system alone, measure the same set of samples over several times.

Uniformity describes the color variation as a function of position on the medium. Sometimes the non-uniformity is easily visible; most digital printers cannot print a full page of uniform gray without visible streaking. Sometimes it is apparent only to instrumentation; monitors vary significantly in luminance between the middle and the edges but the variation not usually noticed by a typical user. It is also not uncommon for the color of adjacent pixels to affect the color of the measured pixel.

Randomizing the position of the color samples used to measure stability will incorporate a measure of uniformity into the stability measurement. The assumption is that the non-uniformities (which may be systematic) can be modeled as random variations over a sufficiently large number of samples. For color monitors, however, where variation in luminance over the surface of the CRT is not important to the appearance, the recommendation is to consistently measure the same position each time[7]. This avoids including the unimportant variations in uniformity in the stability measurement.

Obviously, the accuracy of the characterization cannot exceed the stability. If the color variations are large, or are visibly systematic (ie. the color adjacency problems in NTSC video) there may be no way to achieve a satisfactory characterization on a per pixel basis.

4.5.2 Measurement Systems

Color measurement systems vary in price and performance. Performance factors that affect characterization are accuracy, precision and speed. These factors will vary as a function of color, so it is important to test these parameters across the full range of the color space used in the application. Another set of considerations are physical. Reflectance colorimeters and spectrophotometers contain a predefined internal light source and measure samples which must be positioned tightly over an aperture. Some even require the sample to be inserted into the instrument.

For measuring printed samples, a digitally controlled x-y stage is convenient for automatically positioning a set of samples under a measurement head. If the measuring instrument has an aperture (rather than a lens) some mechanism must be devised to maintain the proper distance from the head as the stage moves. This can be a problem for instruments that require the sample to press tightly against the aperture.

Most instruments for measuring color monitors fasten to the surface of the monitor. They are designed to be used in a darkened environment so ambient light does not affect the measurement. This does not accurately model what the user sees in a well lit room. To model the effect of ambient light on the display, an instrument with a lens that can be positioned where the viewer normally sits is required.

A spectroradiometer with a focusing lens is the most flexible instrument for characterization. It can be positioned in a typical viewing position in the standard viewing environment. Within the range of the optical system, the distance of the sample from the instrument does not affect the measurement. Unfortunately, it is also the most expensive and difficult to use (though computer driven interfaces are making these instruments simpler to operate). Furthermore, most spectroradiometers are slow, taking several seconds to several minutes per measurement. New technologies, however, will be faster by several orders of magnitude and should be ideally suited to these applications[8].

Spectrophotometers can be used to characterize reflective media as long as the standard light source is one of the sources provided with the instrument. Similarly, reflectance colorimeters that include the standard source can be used as the primary instrument for applications where accuracy requirements are not stringent. Colorimeters also provide a quick way to verify that a characterization is still valid. While the absolute values of the measurements provided by these instruments may not be accurate, they are precise so changes are precisely recorded. There are also colorimeters designed specifically for use on color monitors. There is no internal light source to standardize, so only the required accuracy is an issue for their use.

4.5.3 Model vs. Sample

For most color reproduction systems it is difficult to construct an accurate model that transforms between device coordinates and tristimulus values. The exception is a well calibrated color monitor, though the model does not include the effect of ambient light falling on the face of the monitor. The Neugebauer equations are specific to halftoned printing and require parameters that are difficult to supply in other than tightly controlled environments. Methods based on sampling can be applied across a wide range of media and environments. The idea is very simple; set up the device in the manner in which it is used, generate a set of test colors and measure them. The measurements are used to generate look up tables that define the characterization. The accuracy of the characterization is defined by the stability of the device, the accuracy of the measurements and the density of the sampling.

To provide the most accurate characterization, every producible color should be generated and measured. This is usually a prohibitively large number of samples and measurements, so it is necessary to subsample the color space and interpolate. The density of the sampling and the type of interpolation must be chosen to fit the characteristics of the color space being measured. The result is a sampled function that maps from device coordinates to the standard. This function must then be inverted to provide a mapping from the standard representation to device coordinates.

4.5.4 Sampled Functions

The sampled functions provide a a mapping between an n-dimensional device coordinate system to an m-dimensional standard representation. Typically, $m = 3$ (based on CIE standards) and n =3 or 4. The measurements are used to generate m, n-dimensional functions. For example, assume a three color printer and sample varying cyan, magenta and yellow. This produces three functions: $X = F_X(C,M,Y), Y = F_Y(C,M,Y)$ and $Z = F_Z(C,M,Y)$. The inverse functions need to be $C = F_C(X,Y,Z), M = F_M(X,Y,Z)$and $Y = F_Y(X,Y,Z)$. However, a uniform sampling in X,Y,Z of F_X, F_Y and F_Z does not generate an accurate inverse because the shape of the device gamut expressed in X,Y,Z coordinates is not a cube or even a rectangular solid. Figure 13 shows such a gamut for offset printing. The mesh corresponds to a uniform sampling in C,M,Y, that is, it is a cube in device space. Not only is the uniform mesh significantly distorted, the gamut is concave.

Interpolation is used to find X,Y,Z for a given C,M,Y triple. To find the inverse (C,M,Y given X,Y,Z), we must search in F_X, F_Y and F_Z simultaneously for a solution that matches the requested X,Y,Z triple. The author has found that the shape of the functions can cause instability for Newton's method, so our implementation uses binary search. Techniques based on successive approximation have been suggested elsewhere[35, p. 209].

If the sampling is sufficiently dense, the interpolation can be piecewise linear. One advantage of multi-linear interpolation is that it is straightforward and efficient to implement in hardware[29]. However, as measuring large numbers of samples is tedious without a high performance automated measurement system, higher order functions combined with fewer samples are sometimes used[20, 14]. The high order functions can be either be implemented directly or used to generate sufficiently dense piecewise linear functions.

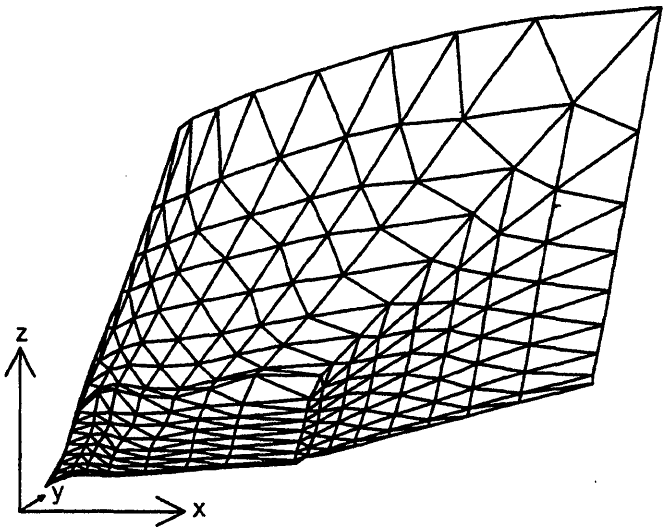

Figure 13: Three-dimensional view of a typical offset printing gamut expressed as tristimulus values, X, Y, Z.

While sampled functions are common in many applications[18], and there have been several implementations of this method to device independent color applications[35, 37, 20, 14, 12] there is no general reference describing in detail how to apply these methods to color device characterization. The sampled functions produced are sufficiently complex, especially when trying to invert them, that further study will be required before such a reference can be written.

5 Gamut Mapping

The goal in color reproduction is to reproduce the appearance of the colors. Color appearance is a more complex than the principles defined in the section on colorimetry. In that section, care was taken to indicate that two colors with identical tristimulus values "look the same" only if the viewing conditions are the same. If the viewing conditions are not the same, colors with the same tristimulus values can look very different. The size of the colored region, its surface characteristics (glossy, mat, opalescence), the color of the surrounding area, what the observer was viewing previously, and so on all contribute to the appearance of the color. Figure 14 demonstrates the effect of background on the appearance of a gray square. The squares are identical, but the one on the dark background appears lighter than the one on the light background.

For an image is viewed on a particular device, the characterization defines the tristimulus values for each color in the image. If each color is accurately reproduced on a different device viewed under the same conditions, reproducing the tristimulus values will generate an image that looks identical. However, if any color must be changed to accommodate limitations in the device gamut, or if the viewing conditions are different, reproducing tristimulus values will not generate an identical match or even the best reproduction. *Gamut mapping* is the process of transforming the image colors to accommodate the differences in device gamut

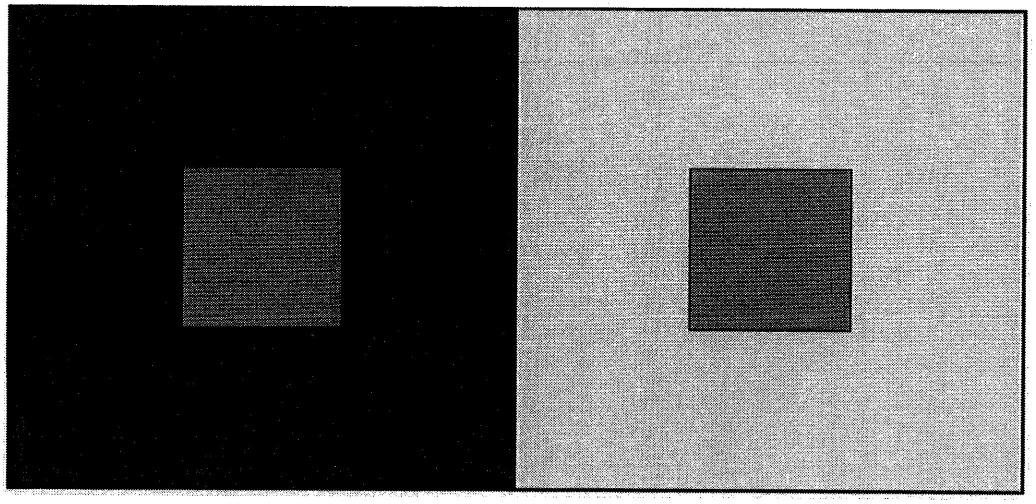

Figure 14: The small gray squares measure the same color, but appear different as a function of background.

and viewing conditions.

The need for gamut mapping to achieve good color reproduction was recognized by Neugebauer, a pioneer in using colorimetric information in color reproduction. In his 1958 article[27], he said that research was needed to determine optimal algorithms for color gamut and tone compression. He also recognized that transformations were needed to accommodate changes in viewing conditions, and that the magnitude of color shifts tolerated varied with the color and the subject. While digital technology has made colorimetric color reproduction technology more readily available and more flexible, these are all still open problems.

5.1 Typical Device Gamuts

Figure 15 shows the gamuts for a typical computer monitor, offset print and transparency film plotted on a chromaticity diagram. For each outline, only the colors in the interior can be reproduced in that particular medium. Typical values for white for each device are also indicated. The monitor and film gamuts are significantly larger than the print gamut. The reduced saturation in the print is typical of reflective media and gamuts for digital printers are similar to the one for offset print. The white point variation between media can be larger than shown. This figure graphically demonstrates that gamut mapping is a requirement for digital color reproduction systems.

Figure 16 shows three views of a monitor and a printer gamut converted to CIELAB coordinates.

This transformation aligns the white points but does not align black. Note that the printer black is not exactly the same hue as white. The difference between the black points of the two gamuts can clearly be seen. While the position of black for the monitor gamut is unrealistically set to (0,0,0) (a result of the simple linear model used to convert to tristimulus values), it is not unusual for different devices to have different black values.

The ratio of the lightness of white to that of black is called *contrast* or *dynamic range*. Differences in contrast correspond to different distances along the L* axis between device black and white. In figure 16, the monitor is shown to have higher contrast than the print. Contrast is a more important consideration for reproduction than absolute brightness because the human visual system's response to differences in lightness is relative. A key

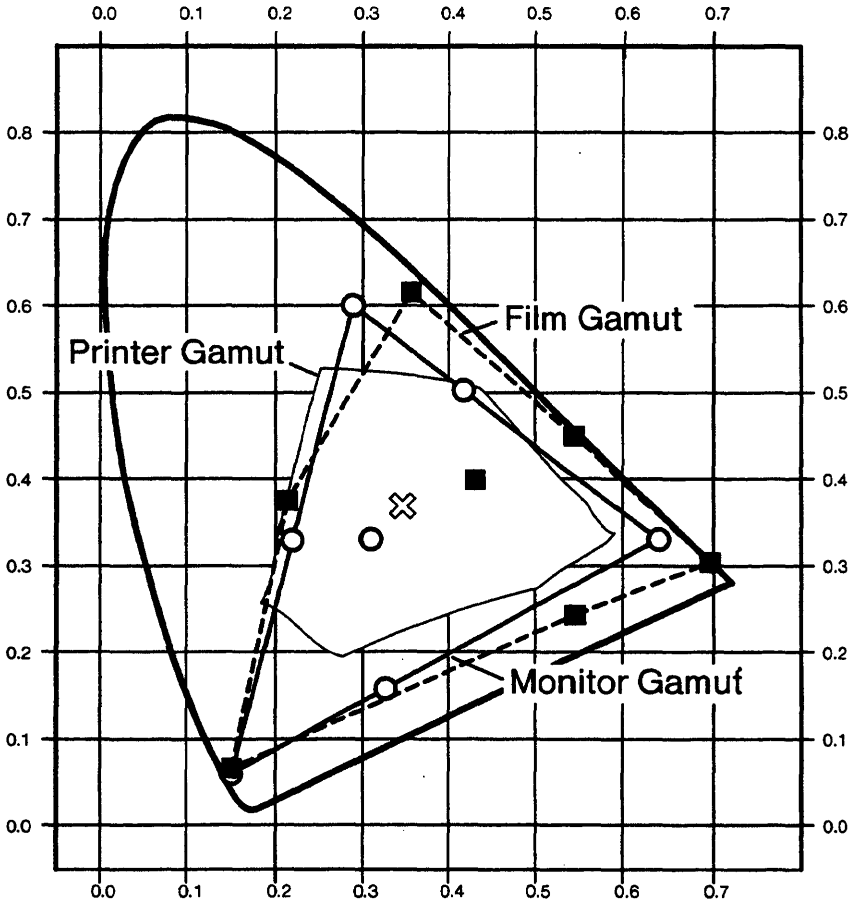

Figure 15: A film, print and monitor gamut plotted on the CIE chromaticity diagram. The outline bounds the gamut, and the symbols mark extremes in the device coordinate system (ie. red, green, blue, cyan, magenta, yellow). Each gamut's white point is marked with a corresponding symbol.

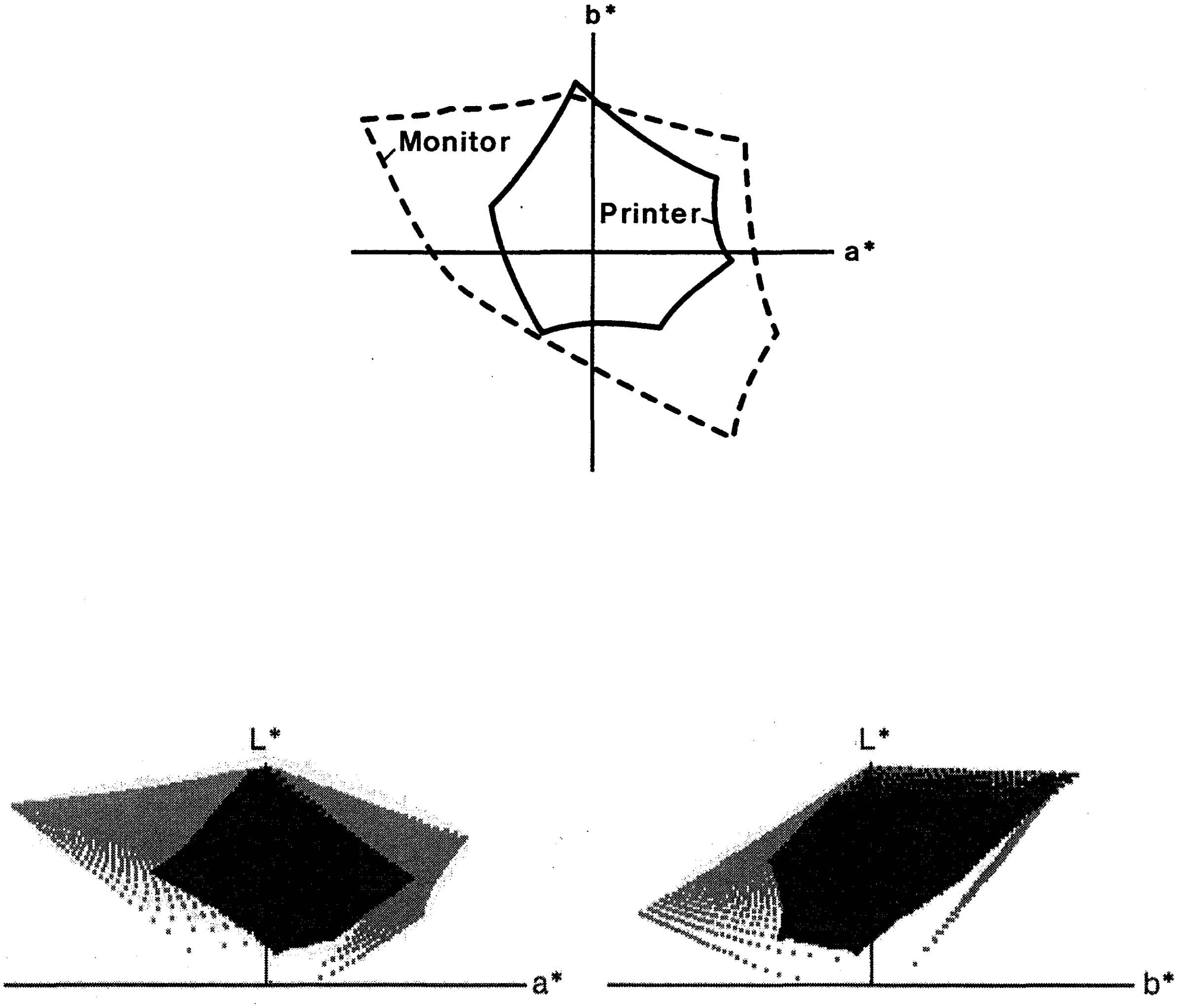

Figure 16: Three projections of a printer and a monitor gamut in CIELAB space. The printer is the solid line in the a^*, b^* projection and the black area in the L^* projections.

part of gamut mapping is adjusting the lightness values in an image to produce the right contrast.

5.2 Black and White

The color "white" is not an absolute one, but is defined as the brightest achromatic color in the viewing environment. Similarly, black is defined as the darkest achromatic color. It is a property of the human visual system that we adapt to the ambient lighting and recognize color relative to the current definition of white. This property, called *color constancy*, is basic to human color vision. The CIELAB and CIELUV color spaces are defined with respect to a reference white for this reason. However, simply representing color in one of these spaces does not adequately model the full effect of varying illumination[2].

For a particular image or illustration, there are some colors which are defined as white and as black, either explicitly or implicitly. A good color reproduction system will usually map these values to the white and black values defined by the target device. Problem images are often ones where the definition of black and white is unclear (as in foggy scenes).

5.3 Tone Reproduction

Tone reproduction defines the mapping of the lightness values in an image. Even assuming black and white are defined, there is an infinite number of ways to map the intermediate values. Traditional graphic arts practice is to make a nearly linear mapping from the density values of the original to the density values in the reproduction[43]. The slope of the mapping function is adjusted to compensate for differences in contrast. In colorimetric systems linear L^* mappings are commonly used[10, 11, 32, 33, 42, 23, 20], though some authors have used mappings based on luminance values[35, 37].

Two things are clear about tone reproduction; it is a critical component of reproduction quality, and the ideal mapping is image dependent. Rules of thumb in the graphic arts literature[44] emphasize that tone reproduction is the most important variable to control for good reproduction, and experience with digital systems confirms this as well. Recent work has resulted in an algorithm that provides adaptive mapping of lightness values[1, 23].

5.4 Out-of-gamut Colors

Image colors that lie outside of the target gamut must be mapped inside the gamut to be reproduced. Figure 17 shows several ways of projecting an out-of-gamut color to the surface of the gamut. The correct method depends on how the color relates to other colors in the image, and it is often unsatisfactory to correct the problem by only changing the out-of-gamut color. For example, if the color is part of a shaded object, either a hue shift or a flat spot in the shading will occur if only the out-of-gamut color is transformed. For some problem situations, the only acceptable solution is to redesign the image. Many systems, therefore, provide an interactive mechanism for handling out-of-gamut colors[35, 40, 42]. Uniformly scaling the gamut to force all colors to lie inside the gamut usually produces excessive desaturation of the image. Some form of partitioning the color space and adaptively transforming each section seems to be a superior approach[23, 17]. It is important the distortions produce no discontinuities in the color space. For colors that are nearly within the gamut, any of the indicated projection algorithms are adequate because the changes are small[35, 37]

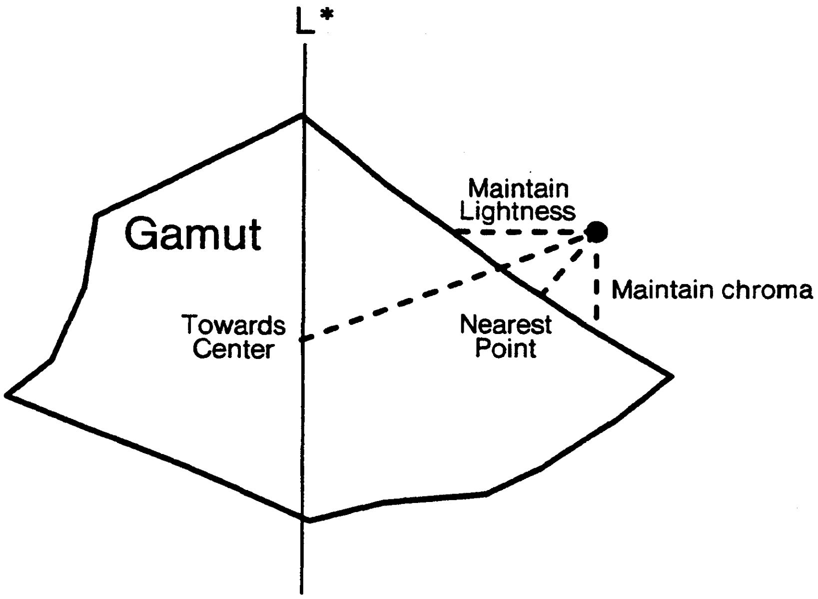

Figure 17: Diagram showing different ways to map an out-of-gamut point to the surface of the gamut.

6 Digital Color Interchange Standards

The tristimulus values, or some transform of them, derived from CIE 1931 Standard Colorimetric Observer is being used as the basis for the device independent digital color interchange standards currently being proposed. This section will provide a survey and references for this work. There is no single standard commonly used in industry today.

6.1 General Issues

A number of issues determine the effectiveness of standard. The first is acceptance, for a standard is useless unless there is a significant user community. Each standard is based on one or more color spaces. It is important that the transformation between the color space and that of common devices is computationally practical. The syntax of the standard should be straightforward to parse, and the the colors must be specified with adequate (though not excessive) precision. A colored image may contain millions of pixels, the color of which must be specified in the standard representation. A lack of precision will cause errors in the color. Too much precision will make the file size unwieldy. Finally, because color specification for device independent color reproduction is inadequately understood, a good standard will contain room for expansion as our understanding of this problem evolves.

6.2 ISO/ODA

The International Organization for Standardization (ISO) is a worldwide federation of standards bodies. Standards are developed through committees and working groups sponsored by ISO. Significant effort has been applied to developing a standard for documents called ODA (Office Document Architecture). A Colour Addendum to ODA has been produced by ISO/IEC JTC1 SC18/WG5 (Working Group 5 of Subcommittee 18 of Joint Technical

Committee 1 of ISO and IEC). It is currently in the final stage of review[15].

It is common in ODA that the document creator may use any convenient specification for document content as long as a method for converting to the standard representation is supplied. The Colour Addendum specifies that color coordinates must be related to the CIE tristimulus values in one of two ways: either a 3 by 3 matrix (suitable for additive color systems) or a n–dimensional lookup table, where n=1, 2, 3 or 4. The intent of the lookup table is to accommodate printing colors systems that use cyan, magenta, yellow and black. However, it is a perfectly general mechanism, up to 4 dimensions of color space.

ODA defines a separation between document architecture and content architecture. Current content architectures are characters, geometric and raster (and more are planned). The proposed model applies across all content levels. For raster content, CIELAB and CIELUV are also recognized.

The subcommittee responsible for ODA (S18, Text and Office Systems) has recognized that it would be advantageous to have a unified representation for color in all the areas it is standardizing. This effort will presumably be a superset of the Colour Addendum to ODA; it's called the "Text and Office Systems Colour Architecture" or TOSCA. TOSCA is in the early stages of design at this point and has little to report.

6.3 Xerox Color Encoding Standard

Xerox has published a general standard for encoding color in digital systems called the Xerox Color Encoding Standard[9]. It contains a set of *color operators* which convert input values to device dependent one. There is a standard RGB operator defined so that a linear transformation can be used to convert colors so specified to CIE XYZ, a linear transformation of RGB called YES (similar to NTSC IYQ) which separates the luminance information into a single channel, and an operator that interprets CIELAB values. The form of the standard makes the interpreter of the operators for each device responsible for converting from the standard to device dependent coordinates.

Each operator definition contains an open field called *appearance hints* that can be used to encode whatever additional information might be required to help reproduce the correct appearance of the color. Once such hint might indicate the source environment (monitor, print or scanner) for the color specification.

6.4 TIFF 5.0

TIFF is the Tagged Image File Format used by Aldus and Microsoft; Version 5.0 supports colorimetric RGB, where the primaries and white point can be specified (SMPTE and D65 are the defaults) along with "color response curves" (for gamma correction).

6.5 TekHVC^{TM}

TekHVC^{TM} is a color spaced derived from CIELUV used in the Tektronix products[42, 25]. Tektronix sells it with a system for selecting colors that allows the user to see the different device gamuts. It is also being proposed as a *de facto* industry standard for color representation across different devices. The changes to CIELUV offered by TekHVC are a rescaling in chroma to provide more uniformity and an automatic rescaling of hue values to keep the values associated with perceptual hues uniform across different white points ie. a hue=0 is always the same color of red in TekHVC, but in CIELUV or CIELAB, hue=0 is different shades of red depending on the reference white used in translating the tristimulus values.

6.6 Postscript^{TM} Level 2

Adobe Systems has announced extensions to the page description language Postscript^{TM} that include a colorimetric color specification[38]. Colors can be specified as tristimulus values (XYZ) or CIELAB values as well as the current set of color models. A full specification will be released in early 1991[31].

7 Discussion

It seems clear that colorimetric color reproduction will become standard for digital systems. However, there are many issues left to resolve before such systems become common. All of the topics discussed in these notes will need further development as they are applied to commercial systems.

Device characterization and calibration are issues for manufacturers of both imaging and color measurement equipment. Makers of imaging equipment need to make their products more stable and easier to calibrate. Makers of color measurement equipment need to make instruments that are fast and computer controlled. It is still very difficult to implement and maintain a fully characterized environment.

Research in gamut mapping should be directed towards image dependent, adaptive methods. While canonical transformations (such as a general purpose monitor-to-print transformation) are useful first steps, higher quality will demand more sophisticated transformation or will continue to rely on a skilled operator. How much can be achieved automatically is an open question.

Many of the problems in color reproduction are application specific; different applications emphasize different aspects of such a system, and there are often several ways to solve a particular problem depending on the goals and expertise available. For example, a soft-proofing system for the graphic arts must meet the existing quality standards in commercial printing and must include functions specific to four-color printing such as gray component replacement. A desktop publishing system directed towards digital printers cannot meet current graphic arts quality standards. However, the standard representation must be generated and decoded by a wide variety of systems, not all from the same manufacturer, so it must be more carefully specified than one that is only used internally.

The type and source of imagery reproduced also affects the system design. Computer generated pictures typically contain less noise and more saturated colors than scanned ones. Less noise means that banding and other quantization artifacts are more visible. Many saturated colors available on monitors are outside the print gamut. However, a digitally generated original can contain semantic as well as a colorimetric description for the colors which makes it easier to automatically generate a good appearance match. In a traditional scan/print systems, the internal representation contains no semantics beyond the color of each pixel.

8 Future Directions

The use of colorimetric characterization for different forms of digital devices is an important step towards device independent color. However, tristimulus values alone provide inadequate information for good color reproduction. More work is needed to determine how to express the missing information.

In many computer graphics applications, a high level description of the scene already exists in digital form. For 3D graphics, this representation will consist of surfaces and light sources. For 2D graphics, a high-level representation is not guaranteed, but may possibly be derived from the tools used to select the colors. For example, the colors may have been selected together as part of a palette. Color gradations are often specified as an algorithm for blending two colors. Future models may well take advantage of this information when considering the problem of cross media rendering

Some investigators are considering reflectance-based representations for color in digital systems[45, 28]. Many factors affecting color appearance can more easily be modeled in terms of surface reflectances than tristimulus values. Work in analysis of real-world surface reflectances[22] indicates that they can be characterized as a linear combination of a small number of basis functions. This makes surface-based representations computationally feasible.

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