COLOR MANAGEMENT RESEARCH AT WESTERN MICHIGAN UNIVERSITY

PAUL D. FLEMING III

Center for Ink and Printability Research, Department of Paper Engineering, Chemical Engineering and Imaging, Western Michigan University Kalamazoo, MI 49008

ABSTRACT

The principles of Color Management are reviewed. The challenges of color matching through multiple productions are presented. The Color Management process is proposed as the path to addressing these challenges. Recent results of novel research at Western Michigan University are shown to illustrate Color Management in action.

1. INTRODUCTION

The issue of managing and controlling color, from scanners to monitors to digital printers/proofers and finally to printing presses, has been an issue ever since the first color image was displayed and printed. Accurate color control is vital in order to have a predictable quality of final product, whether it be printed on a substrate or displayed in an image-editing program or a Web browser.

The advent of digital video and computer-generated animation has further compounded the problem. Accurately matching color, between computer CRT and LCD displays, Analog monitors, Cinematic projection, companion books and wearing apparel, present an apparently insurmountable challenge. To meet this challenge, standards have been established and Color Management methods have been developed. Essential to utilizing these methods are spectrophotometers and colorimeters, which were virtually unheard of by printerstwenty-fiveyears ago. These have now become necessary tools in all media industries.(1-4)

To address the issues of accurate color control throughout the production process, color management (3,4) systems have been developed. The International Color Consortium (ICC) was formed in 1993 by Adobe, Agfa, Apple, Kodak, Microsoft, Sun Microsystems and Silicon Graphics (3-7) to define the standards for color device characterization. This device characterization is presented in terms of specially formatted files, which have come to be called profiles.

Much of the problem of handling color lies in the inherent differences between the mechanisms by which different input, display and output devices process color (8-12).
Computer displays, scanners and digital cameras are generally based on the Additive Color Theory$^{[13-17]}$ and are represented in terms of differing amounts of Red, Green and Blue (RGB). On the other hand, printing ink on substrate is based on the Subtractive Color Theory$^{[14,17,18]}$, which generally employs differing levels of Cyan, Magenta, Yellow and Black (CMYK). The problem is further complicated by the fact that the same RGB image looks different on different monitors, even ones that are nominally identical. Growing acceptance of Liquid Crystal Display$^{[19]}$ (LCD) monitors, in addition to the standard Cathode Ray Tube (CRT) monitors, further complicates the situation. Furthermore, the two color models span different portions, or gamuts, of the visible color space$^{[8]}$. Some colors representable in the RGB space cannot be printed in CMYK space, and vice versa. In particular, highly saturated primary colors are readily displayed, but cause serious problems in printing.

Ambiguities in handling color start first when electronically inputting color into the workflow. Imagine scanning a saturated solid red patch, such as a corporate color. Scanner A may report (Figure 1) the color in terms of RGB (Red, Green and Blue) as (250, 0, 3), while Scanner B reports it as (240, 5, 3). A digital camera may indicate the patch should be (235, 10, 7). Because the CCDs (Charge Coupled Devices) used in scanners and digital cameras are fundamentally different from the phosphors used on CRT (Cathode Ray Tube) displays and filters used for LCD displays, none of the reported colors will be correct on any monitor.

![Figure 1. Different scanners report different RGB values for the same scanned original.](image)

Likewise, different digital printers, proofers and printing presses will produce different looking results when printing the same CMYK values (Figure 2). This results because these devices employ different printing processes, different inks and print on different paper.

In the early days of Color Electronic Prepress systems (CEPS), high-end drum scanners were used with a single printing press in a closed-loop$^{[3]}$ system (Figure 3).
Highly trained skilled specialists adjusted scanner characteristics for color separations and halftones based on press characteristics. Using visual observations and some measurement instruments on carefully chosen test targets, they were able to achieve good color “matching”. When the company traded in the old printing press on a new one, the scanner operator had to start all over again. Color separations intended for an offset press were not correct for a gravure press and vice versa.

(38,67,0,0)

**Figure 2.** The same CMYK value printed on different printers will look different.

**Figure 3.** Illustration of a closed-loop color management system.

Today everybody has a scanner, computer and a color printer. Electronic images come from different places including the Internet, digital cameras, computer generated art and different scanners. They are displayed on different CRT and LCD monitors on Macintosh and PC computers. They are intended for multiple purposes; printed on different printers, proofers and presses and to be read on screen with different applications from CD-ROM, DVD disks and Web pages. This intertwined network of connections is illustrated in Figure 4.
This situation can only be practically handled by an open color controlled system. The necessity of accurately handling these different color devices has led to the development of color management systems\(^5\).

The color managed system is achieved by make use of a universal device independent color Profile Connection Space (PCS). For example, the PCS may be CIELAB\(^{21}\) or CIELAB\(^{21}\). A special type of computer file, called a Profile\(^{22}\), characterizes the behavior of the device in terms of the PCS and specifies how to pass into and out of the PCS (Figure 5). The PCS can be thought of as analogous to the Hub city airport used by airlines to route passengers to and from different destinations. Just as a new city can be added to the airline’s service area, a new device can be added to the mix by merely specifying a profile that gets color information into and out of the PCS.
Figure 5. Open Color Management System with central Profile Connection Space (PCS).

ICC Color Management

*Color Management* comes into place to assure consistence color transformation and appearance across assorted color devices or media \(^{(3)}\). The ICC defines standards that can be used for characterizing devices, which then were represented in special computer files called *Profiles*. \(^{(22)}\)

Controlling and achieving reliable color reproduction across different devices is the main goal of color management systems (CMS). The foundation of this is what are called the 4 Cs of Color Management. \(^{(23)}\) These are Calibrating, Characterizing, Consistency and Converting. Each device needs to be calibrated prior to characterizing and without consistency, this process is of little value. Device calibration involves adjustment of device response in order to match an established condition \(^{(3, 7, 23)}\). Characterizing the device involves using instruments, such as a colorimeter and spectrophotometer, to measure the device response for color signals (from color test charts) that are sent to it. Because of this procedure, the gamut of the device is calculated and the characterization data are used to create an "ICC Profile", which is an important part of the CMS \(^{(24)}\). The *converting* process involves converting an image between two different color spaces via the ICC profile. For instance, a printer profile would be employed to convert a displayed RGB image into...
printer CMYK color space, in order to print it \(^{(23)}\). Therefore, an accurate ICC profile would results an accurate color conversion between different color spaces.

Transforming color information from one medium to another, i.e. from one color space to another (such as from monitor to printer) can be accurately achieved if the calibrating and characterizing procedures of the media have been accurately accomplished. \(^{(7)}\) To facilitate this transformation, a combination of application software (such as Photoshop), operating system software (such as ColorSync for Mac OS or WCS and ICM for Windows) and Color Management Modules (CMM) are used.\(^{(22)}\)

In the following sections, recent research at Western Michigan University is reviewed.

**ICC Profile Construction**

Here we discuss recent work on manual construction of ICC profiles without aid of commercial software. This involves development of customized software, written in C++, to read and write ICC Profiles. Details are given elsewhere \(25{-}28\), but notable results are reviewed here. In working with ICC profiles over the past decade, we have often seen irregularities in profiles constructed with commercial software. Such irregularities include “dimples” and “pimples” on gamut boundary plots \(29\), “islands” of disjointed gamut volumes and crossing boundary lines for slices of constant luminance. These may result from underfitting or overfitting training data or singularities in device models. It is virtually impossible to determine which of these causes is producing the irregular results with profiles constructed with proprietary software. Thus, we have the need for our own construction and device model methods to find sources of such irregularities and eliminate them.

A crucial property of any transformation between any two color spaces is that the transformation be continuous and smooth. Since human color perception is three-dimensional \(13{-}18\), this means that the transformation between any pair of three-dimensional color spaces must be 1-1 and invertible within the device gamut. The necessary and sufficient condition for this is that the Jacobian determinant \(30\) of the transformation must not change sign for any color value within the device gamut.
For example, we consider a transformation $P$ between RGB and XYZ:

$$ T = P(A), $$

where $\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}$ is the vector of tristimulus values and $\begin{bmatrix} R \\ G \\ B \end{bmatrix}$ is the vector of RGB values.

The Jacobian matrix is given by:

$$ J_P = \begin{bmatrix} \frac{\partial x'}{\partial R} & \frac{\partial x'}{\partial G} & \frac{\partial x'}{\partial B} \\ \frac{\partial y'}{\partial R} & \frac{\partial y'}{\partial G} & \frac{\partial y'}{\partial B} \\ \frac{\partial z'}{\partial R} & \frac{\partial z'}{\partial G} & \frac{\partial z'}{\partial B} \end{bmatrix}. $$

The Jacobian determinant is given by

$$ J = \det J_P $$

Thus, the condition that the transformation is 1-1 and invertible is that $J_P$ is positive definite and $J$ is always positive. This means that any model for this transformation must satisfy this condition. Thus, it is necessary to constrain the model to either apriori satisfy the condition or constrain it to satisfy the condition.

Example 1 – Scanner

We consider a general quadratic scanner model for $T$ in terms of $A$. The Kodak IT8.7.2 (Q60 R1) was scanned with an Xrite II/IO scanning spectrophotometer. The same chart was scanned with an HP ScanJet G4050 at 300 dpi and the image file was saved as a Tiff (Tagged Image File Format) file. The tristimulus values from the spectrophotometer were fit to a general quadratic form in the scanned RGB values of the corresponding patches. The resulting fit gave negative tristimulus values for the black point, so the measured black point vector was subtracted from the $T$ vector and the resulting vector fit to a linear plus quadratic form in $A$ with no intercept. The Jacobian for this transformation was always positive, so the model was used to construct a scanner profile. It is not necessary in practice to be able to invert a scanner transformation, but a non-invertible would imply a non-physical scanner color space.

Figure 6 shows the comparison of the color gamut plot in chromaticity space for the quadratic profile compared with a profile built using X-rite ProfileMaker 5, using the same training data. Note the smooth regular behavior for the gamut boundary for the quadratic profile versus the ProfileMaker profile that has “humps” on the gamut boundaries.
Figure 7 compares 3D plots of the profile's gamut volume showing every point inside the CLUTs (Color Look Up Tables) used to construct the profiles. This contrasts the smooth regular behavior of the points with the quadratic model based profile, with spurious points with the ProfileMaker profile.

![Figure 6. The gamut volume of icms profile (A) and ProfileMaker profile (B).](image)

Example 2 – Monitor

A Mac Pro tower with Dual Quad 2.26 GHz Xeon processors and two LCD displays attached to it was chosen for Monitor profile studies. One display has a fluorescent backlight and the other has a LED backlight. The training data were measured using the LCD chart provided by X-rite with ProfileMaker. As with the scanner model, the
training data were fit to a general quadratic model for both displays. Again, the fit black point exhibited negative values, so the measured black point tristimulus values were again subtracted and the data were refit to a no intercept model. The models were then used to calculate the CLUT entries for each display.

Figure 8 shows the gamut boundary plots on the chromaticity diagram for the two monitors with the quadratic model plot compared with the corresponding profiles calculated from 11-Profiler, Xrite’s newest profiling software. We see that the 11 profiler and quadratic models have virtually identical chromaticity gamuts.

![Figure 8. The xy-chromaticity plots comparisons of different profile types for Apple (A) and Acer (B) monitors.](image)

**Digital Proofing of Spot Colors**

Color Management methods, discussed above, have facilitated digital proofing of process colors.\(^{(31)}\) This is because modern inkjet printers have large color gamuts when used with special proofing paper \(^{(29,32)}\). Spot colors, on the other hand are designed to match corporate colors or other saturated colors not matchable with CMYK. Spot colors are premixed to obtain the desired color and are generally more transparent than process color inks \(^{(33)}\). However, no ink is perfectly opaque, so the color of trapped, overprinted spot colors must be taken into account when designing a print job with spot colors and proofing of press run. Details of the proofing process are given elsewhere \(^{(32,34-37)}\), but some results are summarized here.

A flexographic spot-color press trial was run on the Mark Andy/Comco Commander in the Western Michigan University Printing Plant. Four solvent-based spot color inks were chosen, Red, Green Blue and Orange. The opacities were measured prior to printing and are given in Table I.
Table I. Opacity values of the four spot color inks

<table>
<thead>
<tr>
<th>Spot Color</th>
<th>Blue</th>
<th>Green</th>
<th>Orange</th>
<th>Pink</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solvent Based Ink</td>
<td>6</td>
<td>12</td>
<td>6</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 9 shows the flexographic photopolymer plates with various press and printing related symbols, including impression pressure marks, vignettes and solid color patches. The substrate used was a C1S-SBS board. The viscosity of the inks was kept constant at 22 seconds on a #2 Zahn cup over the period of the press run. The speed of the press was set to 50 feet/min.

Figure 9. Plate design for flexo press trial.

The overprint test charts were output to two different digital printers; Epson Stylus Pro 7900 and Epson Stylus Pro 9800. These two digital printers differ in their ink sets. An Epson Stylus Pro9800 has K3 UltraChrome ink technology with eight colors, whereas an Epson Stylus Pro7900 has additional inks of orange and green along with the eight color set. Different proofing workflows, color managed Adobe Photoshop, Adobe Photoshop with SmartColour (34-37) iVue plugin, and the CGS ORIS RIP (32) were employed.
The CIELAB values were measured for both the press printed sheets and proofed test charts on digital printers using MeasureTool software and an X-Rite i1-iO scanning spectrophotometer with 45°/0° geometry. The press sheet CIELAB values were considered as reference and all the ΔE calculations were done using formula $\Delta E_{\text{CMC}}^{(2:1)}$ \footnote{38}. These reference press sheet CIELAB values are the average values of three different sheets printed on press for each individual patch. The standard deviation for all 264 patches measured for three press sheets was in the range of 0.05-0.15.

The proofing results for two color overlap patches for various software solutions are compared in Figure 10, it can be seen that the iVue produced the best results followed by the RIP and then Photoshop.

**Figure 10.** Graphical values of $\Delta E_{\text{CMC}}^{(2:1)}$ color differences between flexo press and digital printers for two color overlap patches.

**SUMMARY AND CONCLUSIONS**

We have reviewed the basis of Color Management. The challenges were enumerated and how Color Management addresses these challenges was discussed. How the process addresses the challenges was described. We have reported some results of recent novel research in our group at Western Michigan University.
REFERENCES


