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Life of a Color – The Management of a Color

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Abstract

Color management is the process by which colors are described, communicated, transformed and reproduced using a device independent color representation. Traditional color management has used only CIEXYZ colorimetry based on a single observer (the 1931 Standard 2° observer) and single illuminant (D50). A new color management system is described (iccMAX) that accounts for a complete color process from light sources onto objects captured through color matching, and provides the means to add perceptual aspects of color..

Introduction

There are three key aspects to Color Management: asking the right questions about color, providing answers to the questions that you come up with, and finally communicating everything. The main focus of this paper involves the asking of questions about color and how they can be answered by Color Management Systems based on specifications [1] defined by the International Color Consortium (ICC).

The explicit details about how things are encoded and communicated are provided at great length by these specification documents. It is therefore recommended that those interested in such details refer to the specification documents directly.

In considering questions about color there are four general questions that come to mind:

- *What is it?*
- *How is it formulated, controlled, or made?*
- *What does it look like?*
- *How does it relate to or interact with light?*

Various relationships exist between these questions, and the extent to which these questions can be asked and answers provided distinguishes various aspects of color management systems.

Basic Color Management

To explore the use of asking and answering color related questions let's consider a basic color management situation. We have an image on a display that we would like to print out on a printer (Figure 1).

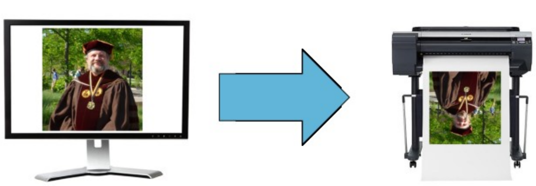

Figure 1 – Basic color management situation – Printing a displayed image

There are several questions that can be asked related to this basic color management task, but one of the most direct questions would be:

- *What amount of Cyan, Magenta, Yellow, and blacK (CMYK) ink is needed to match the Red, Green, and Blue (RGB) pixels on the display?*

By asking and answering this question for each RGB pixel on the display one can determine the proper amount of ink to get a matching reproduction on the printer.

However, the background details to this question also refer to a specific display, and a specific printer with a specific paper and specific inks printed in a specific manner. To support differences to any of these specific details a different answering mechanism is needed – which can quickly become unwieldy. To simplify things we can reformulate this question into two separate questions:

- *What does a pixel with a RGB value "look" like?*
- *How much CMYK ink is needed to get the same "look"?*

Separate answering mechanisms can be defined for each of these two questions, and then the appropriate mechanisms can be combined to perform color reproduction from any display to any printer/ink/paper combination. In the world of color management this is referred to as using device independent color.

However, the challenge in formulating and answering these device independent color questions is finding a way to quantify the word "look" in these questions.

Quantifying Color

Color easily becomes an amazingly complex topic when various details are considered. Ultimately, color is a perception resulting from a sequence of events. A high level view of the process of getting to color perception is pictured in Figure 2.

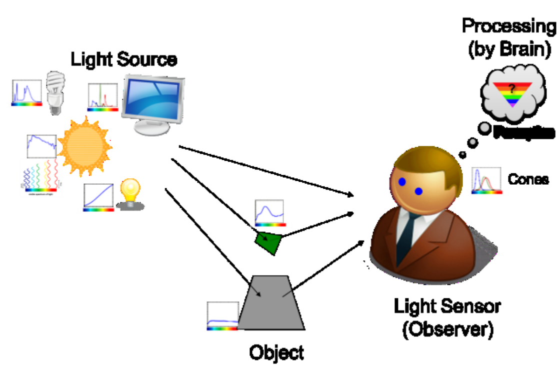

Figure 2 – Aspects of Color Perception

Color perception begins with a source of light that emits photons of electromagnetic radiation that have a distribution of various wavelengths. This emitted light is either observed directly, or it interacts with surfaces before reaching the observer. In interacting with objects, the photons of light can either be absorbed by the objects or they can be in some fashion reflected or transmitted through the object.

Once light gets to the observer the visual system has sensors (cones) that have various sensitivities to different wavelengths of light. There are three general ranges of color sensitivity in the human visual system. Upon detecting photons of light these sensors send combinations of signals to the visual processing portion of the brain which performs the task of color perception.

It is important to remember that the process of getting to color perception involves all four parts: light, objects, sensors, and processing by the brain.

Aspects of these parts are utilized to quantify color in mathematical formulae.[2] The color matching equations in (Eq. 1) define numeric values (XYZ) that can be used determine if two colors match under identical viewing conditions (i.e. under identical lighting by the same observer).

$$X = 100 \frac{\int s(\lambda) r(\lambda) \cdot \bar{x}(\lambda) d\lambda}{\int s(\lambda) \cdot \bar{y}(\lambda) d\lambda}$$
$$Y = 100 \frac{\int s(\lambda) r(\lambda) \cdot \bar{y}(\lambda) d\lambda}{\int s(\lambda) \cdot \bar{y}(\lambda) d\lambda}$$
$$Z = 100 \frac{\int s(\lambda) r(\lambda) \cdot \bar{z}(\lambda) d\lambda}{\int s(\lambda) \cdot \bar{y}(\lambda) d\lambda}$$

(Eq. 1)

where, λ represents wavelength; $s(\lambda)$ represents the spectral power distribution of the illuminant by wavelength; $r(\lambda)$ represents the spectral reflectance of an object by wavelength; and $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ represent color matching functions by wavelength for the "standard" 1931 observer with a 2° field of view.

These XYZ values (or tristimulus or colorimetric values) define a measurement of color for a specified illuminant and observer. Note: It is important to remember that these values will change if either the illuminant or observer changes, or in other words - objects do not have a singular XYZ value.

It can be shown that equal distances between XYZ values do not correspond to equal perceptual differences between colors. Therefore, several mathematical transformations of XYZ values have been devised to define color coordinate values that have a more perceptually uniform distribution. In 1976 the CIE developed a series of equations (Eq. 2) that defines a coordinate system L*a*b* (or CIELAB) that allows the perceptive concepts of lightness, chroma, and hue to be expressed.[2]

The L* axis can be thought to represent lightness, the a* axis transitions from green (-a*) to red (+a*) extremes, and the b* axis transitions from blue (-b*) to yellow (+b*) extremes. Combinations of a* and b* define intermediate colors and neutral (grayscale) colors are described when a* and b* are both zero.

L*a*b* values are defined using a normalization by the XYZ values of the illuminant (the X_n, Y_n, Z_n). Therefore, L*=100, a*=0, and b*=0 defines white regardless of the illuminant. This is convenient, but doesn't necessarily reflect actual color adaptation by human observers.

$$L^* = 116\, f(Y/Y_n) - 16$$
$$a^* = 500\left[f(X/X_n) - f(Y/Y_n)\right]$$
$$b^* = 200\left[f(Y/Y_n) - f(Z/Z_n)\right]$$
$$\textit{where}:$$
$$f(t) = \begin{cases} t^{1/3} & \text{when } t > \left(6/29\right)^3 \\ \frac{1}{3}\left(\frac{29}{6}\right)^2 t + \frac{4}{29} & \text{otherwise} \end{cases}$$

(Eq. 2)

ICC Color Management

The color management questions that were used to describe the color reproduction situation in Figure 1 can now be restated by substituting a numeric representation of color for the word "look" as follows:

- *What XYZ/L*a*b* value does a RGB value have?*
- *How much CMYK ink is needed to get the same XYZ/L*a*b* value?*

In the early 1990's a color management system based on the use of these questions was developed and standardized by the International Color Consortium [2] later becoming in 2005 the international standard known as ISO 15076-1.[3] It defines a profile file format (version 4) as a standard container for specifying color management that has been successfully used widely around the world (though predominantly in graphic arts workflows).

ICC profiles are binary files whose data structures define transforms that can be used to determine answers to the above color management questions. Thus to perform the color reproduction described in Figure 1 the following transformation steps are performed by an ICC Color Management Module (CMM) using transform tags with ICC profiles as follows:

1. A transform tag from the input profile (associated with the display) is applied that converts RGB to XYZ (answering the question: *What XYZ/L*a*b* value does a RGB value have?*).
2. The CMM converts XYZ to L*a*b* values using (Eq. 2). In this case the XYZ and L*a*b* values are used as Profile Connection Spaces (PCSs).
3. A transform tag from the output profile (associated with the printer+ink+paper) is applied that converts L*a*b* values to CMYK ink values (answering the question: *How much CMYK ink is needed to get the same XYZ/L*a*b* value?).*

Rendering intent values are used to define which transform tags to use from the profiles, thus determining preference in how the color management should be performed.

The transforms in version 4 ICC profiles are defined using a fixed set of operations in a fixed order with the ability to leave out some operations as required. For the input side of ICC profiles this is performed basically as follows:

1. Input device channel values are individually transformed on a channel by channel basis using interpolated 1-dimensional curves or 1-dimensional functions.
2. An N-dimensional lookup table (LUT) is applied which represents an even spaced sampling of the transformation

of input channels defined in a multi-dimensional table. Interpolation is used to determine intermediate results between sampled points.

3. These results are then individually transformed on a channel by channel basis using interpolated 1-dimensional curves or 1-dimensional functions.
4. A simple (linear) combination of the channels is performed (by applying a matrix).
5. These results are finally individually transformed on a channel by channel basis using interpolated 1-dimensional curves or 1-dimensional functions.to get the final results.

For the output side of ICC profiles these steps are performed in the reverse order.

An ICC profile can also provide the ability to answer the first question that was posed (i.e. *What amount of Cyan, Magenta, Yellow, and blacK (CMYK) ink is needed to match the Red, Green, and Blue (RGB) pixels on the display?*) as a device link profile – which uses the same transform sequence as described for the input side of ICC profiles.

Limitations of version 4 (and earlier) ICC profiles

Even though version 4 ICC profiles provide a basic platform for developing color management solutions they do have limitations that minimize the ability to pose and answer color management questions.

- *Limited ability to answer the question "What does it look like?"*

The XYZ and L*a*b* color spaces used by ICC version 4 profiles are required to use a single daylight light source (D50) for a single observer (the 1931 Standard 2° observer). Additionally, surface colors are assumed to reflect light uniformly in all directions.

- *Unable to directly answer the question "How does it relate to or interact with light?"*

Because device independent color is only encoded in terms of XYZ and L*a*b* in ICC version 4 profiles with a fixed illuminant and observer, various relationships to how light is interacted with cannot be directly communicated.

- *Limited ability to answer the question "What is it?"*

ICC version 4 profiles are limited to answering "What is it?" using device link and (to some extent) named color profiles. This is exacerbated by the fact that complex transforms cannot be encoded.

Additionally, for some lightweight workflows, ICC version 4 profiles provide too much information as color transforms must always be encoded in a profile.

- *Limited ability to define transforms*

As stated earlier, answering questions about color is further limited by the fact that ICC version 4 profiles encode transforms in a fixed order with a limited set of transform elements. Thus, transforms are limited to "simple" interpolation which is effectively limited to low dimensionality.

Workflow Limitations

As a result of these limitations there are various color workflows that can simply not be addressed using ICC version 4 profiles. One example (of many) is package printing. Using more than 6 or 7 inks is not viable due to the LUT structure. The spectral nature of spot inks cannot be communicated meaning appearance under differing lighting cannot be guaranteed. Gloss and metallic inks reflect light differently based on viewing and lighting angles and therefore overall appearance and predictability in printing cannot be provided.

Introducing iccMAX

In July 2016, the ICC released a color profile specification known as "iccMAX" [4] that was the result of nearly ten years work by the Architecture Working Group (AWG) of the ICC. Aspects and guiding principles of this work included: understanding various color workflows either not addressed or difficult to implement using version 2 and 4 profiles; providing open, cross-platform, vendor-neutral solutions; opening ICC color management to new industries; creating specification documents; and providing a reference implementation.

The iccMAX specification builds upon concepts and principles established in the version 2 and 4 specifications in a similar fashion to adding additional building blocks and pieces to a simple set of LEGO™ blocks. It provides for compatibility with existing profiles while providing additional functionalities and capabilities. Thus, if all you want to do is something simple the simple pieces are there and that is all that is needed, but having a larger collection of blocks allows new rules to be invoked and new color workflows to be implemented.

A central concept to iccMAX is that it provides a platform on which color workflows can be defined. It is envisioned that subset requirements documents known as Interoperability Conformance Specification (ICS) documents can be established to provide the means of defining color workflows that do not require all the pieces of iccMAX to be implemented or utilized. This is akin to defining simpler LEGO™ kits for specific purposes from a larger collection of blocks.

For iccMAX this allows for vertical color imaging markets to be directly addressed without impacting other markets. Additionally, having workflows based on subsets allows the platform of iccMAX to be expanded to address future markets as needs arise.

High level iccMAX Overview

Providing an in depth understanding of the features and specifics of iccMAX is beyond the scope of this paper. From a high level perspective iccMAX provides color space extensions, processing element extensions, hierarchical tag structures for greater extensibility, and other additional tag types to meet various color workflow needs. It is recommended that interested parties consult the iccMAX specification, ICS documents, and other supporting documentation for a greater understanding of the specifics of iccMAX.

iccMAX profiles can be represented in two ways. The binary representation defined by the iccMAX specification document provides a compact binary format for embedding and communicating about color. Additionally, the iccMAX reference implementation (RefIccMAX - developed by the ICC) provides tools to convert between the binary representation defined by the iccMAX specification and an XML representation which is more easily human readable. Using an XML representation of iccMAX profiles provides the means of editing and directly creating some iccMAX profiles without having to have complex tools.

Using iccMAX to answer color management questions

Rather than providing specific details about the iccMAX specification it was felt that a better understanding of some of the power that iccMAX provides would be better demonstrated by showing how various color management questions can be more directly answered using iccMAX (which cannot be answered using ICC v4 profiles).

- *What XYZ/L*a*b* value for a particular observer under a particular illuminant does this pixel value have?*
- *What device values are needed to get a XYZ/L*a*b* value for a particular observer under a particular illuminant?*

These are more specific questions for defining color management that take into account specific lighting and observers. Color matching functions for an observer as well as the spectral power distribution of the illuminant/light source can be defined in an iccMAX profile. Thus arbitrary observers and lighting conditions are supported by iccMAX profiles.

- *What is the XYZ/L*a*b* value for an RGB pixel that has a specified color encoding space?*

Camera manufacturers expressed a desire for simplified profiles that only specify the color encoding space of the pixel (i.e. "It's sRGB"). Color encoding space profiles in iccMAX only contain a rudimentary header and tag that identifies the color encoding space, and the CMM determines the appropriate transforms to apply.

- *How do I convert XYZ/L*a*b* values for one observer and illuminant to XYZ/L*a*b* values for a different observer and/or illuminant?*

Support for arbitrary observers and illuminants is provided by Profile Connection Conditions (PCC) tags in iccMAX profiles that an iccMAX capable CMM uses to make conversions when needed. PCC tags can be populated using a simple Chromatic Adjustment Transform (CAT) or using a more advanced Color Appearance Model (CAM) to adjust for differences in illuminant. Alternatively, a Material Adjustment Transform (MAT) is appropriate for accounting for changes in observer and/or illuminant. MATs are defined based on a color equivalence represented and defined using "Wpt normalization".[5]

- *How is light absorbed / reflected / transmitted by a surface with specific device values?*
- *What device values are needed to get light absorbed / reflected / transmitted in a specific way?*
- *How do XYZ/L*a*b* values change as the observer and/or illuminant change?*

The first two of these questions can be used to define a device independent color management system based on how light interacts with surfaces which is observer and light independent. iccMAX profiles can be connected using spectrally based color spaces.

Answering the third question involves making a connection between spectral representations and colorimetric representations of color (providing compatibility with older version 2 and 4 ICC profiles). An iccMAX CMM applies observer and illuminant information as needed using Profile Connection Conditions (PCC) to determine XYZ/L*a*b* values. This allows application of observing conditions to be deferred to the time when profiles are applied (rather than when the profiles are created).

- *How do you manipulate spectral reflectance?*

Answering this question becomes important when trying to perform spectrally based color management. Derhak's PhD work outlined a simple (linear) method that can be applied to estimate and manipulate spectral reflectances using associated characteristic spectral reflectances on a hue by hue bases with polar Wpt coordinates.[5]

iccMAX profile creators can incorporate these techniques to perform spectrally based gamut mapping, color rendering, or adjustment in abstract profiles. Additionally spectral reflectances can easily be estimated directly from sRGB.

- *How is reflected light affected by the use of a substrate with optical brighteners or printed using fluorescent inks?*

Fluorescence occurs when wavelengths of light are changed by a surface (rather than just being absorbed or reflected).[6] Substrates with optical brighteners and fluorescent inks appear brighter as a result. Special measurement devices and transform logic are therefore required to handle fluorescence correctly. iccMAX provides support for both modeling and characterizing situations where fluorescence occurs.

- *How do you handle lots of device channels?*

Up to 65535 color channels can be supported by iccMAX color workflows through the use of various processing elements in multiProcessElement based tags. Thus iccMAX provides a powerfully flexible way of directly "programming" color transforms which can result in smaller and potentially more accurate profiles (especially with lots of device channels).

- *How does reflected light change as lighting and viewing angles change?*

Glossy, metallic or pearlescent surfaces reflect light based on both lighting and viewing angles with texture providing additional variability in how light is reflected. iccMAX provides the ability to communicate, model, and characterize how light reflects off a surface based on lighting and viewing angles with optional inclusion of texture maps to provide a more complete understanding of color appearance.

- *What is the spectrum of light coming off a monitor?*

This question will become more important as display technology evolves to get larger and larger gamuts. New quantum dot display technology results in emission spectra with larger gamuts that have narrower emission bands.[7] However, variability in appearance of these displays by observers becomes much greater due to normal variability in observer sensitivity functions (color matching functions). For color critical work it may become increasingly more important to have observer specific color management when using these displays.[8] iccMAX provides support for both spectrally modeling displays as well as applying observer specific sensitivity functions.

- *How does light from a video display change due to position and viewing angle?*

Various display technologies often change color appearance based on where you are looking from as well as where you are looking at the display. iccMAX provides support for both modeling and characterizing display output based on relative display location and viewing angle.

- *How is light reflected by a tint of a named color?*

Information about spot colors and other color libraries can be encoded using named color profiles, and iccMAX named color profiles allow output device values, XYZ/L*a*b* values, reflectance/transmittance/fluorescence values, opacity/overprint characteristics, and information about how light changes by viewing and observing angle (BRDF) to be encoded on a tint by tint basis with interpolation used to find values for intermediate tints. Texture maps can also be encoded for named colors thus allowing for 3-D modeling surface color libraries to be encoded as iccMAX named color profiles.

- *What is the probability that a pixel of a multi-spectral image contains a specific material?*

This is an example of posing a "What is it?" question. Multi-spectral images have multiple data channels for each pixel, and identification transforms are applied to determine various material probabilities of things like biomarkers (in medical imaging), surface features (in satellite imaging), or pigment concentrations (in fine art imaging/conservation). Visualization can then be performed based on these material identifications. iccMAX provides support for both material identification as well as visualization.

- *How does iccMAX help with Package Printing?*

The color management needs of package printing are much better met using iccMAX profiles. Spot colors can be spectrally defined with any number of colorants being supported using a multi-processing element to estimate spot color overprints. Additionally, directional effects of gloss and metallic inks can be modeled, and previewing and matching can be performed under a variety of observing conditions by applying observer and illuminant changes.

Wrap-up

The complexities of the color in the real world are encompassed by iccMAX. It provides an extendable platform for modeling and defining color management workflows with backwards compatibility with existing legacy profiles. iccMAX provides the means of answering various questions related to color including:

- *What is it?*
- *How is it formulated, controlled, or made?*
- *What does it look like?*
- *How does it relate to or interact with light?*

The iccMAX specification has been released by the International Color Consortium (ICC) and workflow specific ICS documents are under development. Additionally, an effort is underway to make iccMAX an ISO standard.

With these standards in place, various individual companies have begun the process of evaluating and implementing iccMAX features into their products – however this will likely take time.

To help with this the ICC is providing and promoting educational opportunities for developers (ICC DevCon) as well as providing an open source reference implementation (RefIccMAX) to help speed up the development process.

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Author Biography

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Max is the Principal Scientist at Onyx Graphics where he leads the Color and Technologies team. Steeped in color, Max also serves as Co-Chair of the ICC and Chair of the ICC Architecture Working Group, led the development of the iccMAX specification and maintains the open source RefIccMAX as well as SampleICC and IccXML projects.

Max is also the 2016 recipient of the ISCC MacBeth award.