The Creation of the sRGB ICC Profile

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Abstract

This paper describes transforming the sRGB color space standard into an ICC profile. This sRGB ICC profile provides a clear bridge between implicit color management and explicit color management and illustrates the complementary nature of these two approaches. The paper starts by reviewing the current status and content of the sRGB color space standard. It also very briefly reviews the status of the current ICC profile specification. A series of practical considerations are then discussed that were addressed in order to transform a color space standard into an ICC profile. This paper will also discuss several false starts in this transformation and why these efforts were unsuccessful and the consequences to other software and hardware in the market today. This profile was extensively tested and reviewed by a number of companies and this test process is described. A detailed review of the final sRGB ICC profile is provided. Finally, recommendations to other profile builders and the ICC are given in order to make this process more efficient and accurate in the future.

Current Status of Specifications

SRGB

While the ICC provides a robust, flexible, complex color management solution, many markets can be adequately addressed by a well-specified monitor color space. Currently there are a plethora of such formal and informal RGB spaces, including NTSC, PAL, HDTV, NIFRGB, Apple RGB, SGI RGB, and many, many others.

Two years ago Hewlett-Packard and Microsoft agreed that each needed a single RGB space ubiquitous throughout each company. Hewlett-Packard in particular has a long history of internal color standards including PCL and ColorSmart. After some negotiation, both companies agreed to collaborate on this effort. Hewlett-Packard and Microsoft developed and began to propose the addition of support for a standard color space, sRGB, within Microsoft products (including operating systems), HP products and the World Wide Web. During the last three years Hewlett-Packard, Microsoft and many other premiere imaging companies and individual color experts have been actively refining and supporting the progress of this proposal through a formal international standardization process. The current status of the draft standard is a committee draft for vote stage (CDV) in the IEC TC100 61966 Project Team.[1] This is equivalent to the formal draft international standard (FDIS) stage in ISO terminology. It is hoped that the final international standard will be formally published in early 1999.

The aim of this color space is to complement the current color management strategies, particularly ICC, by enabling a simple method of handling color in operating systems and the World Wide Web. This method utilizes a simple and robust color space definition that will provide good quality with minimum transmission and system overhead.

Current Status of ICC Specification

The purpose of the ICC is clearly stated in its specification. "The International Color Consortium was established in 1993 by eight industry vendors for the purpose of creating, promoting and encouraging the standardization and evolution of an open, vendor-neutral, cross-platform color management system architecture and components."[2] These vendors represented the major platform vendors interested in color management (Apple, Adobe, Microsoft, Silicon Graphics, Sun and Taligent) and two active color management vendors interested in open standards (Agfa and Eastman Kodak). The German graphic arts institute, FOGRA, was an honorary founding member. This honor acknowledges the critical role FOGRA played on initiating these activities.

The major effort to date has been the creation of the ICC profile format. The intent of the ICC profile format specification is "to provide a cross-platform device profile format. Such device profiles can be used to translate color data created on one device into another device‘s native color space. The acceptance of this format by operating system vendors allows end users to transparently move profiles and images with embedded profiles between different operating systems. For example, this allows a printer manufacturer to create a single profile for multiple operating systems."

During the last three years, the ICC has made little progress in formal standardization. Several ICC working groups are active in this area, including a reference implementation working group. If these working groups are successful and their results are adopted by the general ICC membership, it appears that the ICC could be ready to propose its profile format specification as a formal standard within the next 24 months.

Complementary Nature of sRGB and ICC

A clear, complementary usage path between sRGB and ICC color management is a priority. Microsoft and HP are publishing a free "golden standard" sRGB ICC profile to help integrate ICC and sRGB within a single color management system.

Both companies believe that there are some situations where embedding an ICC profile, even an abbreviated profile, is not practical. Both companies strongly support ICC and are not only implementing products supporting ICC, but are actively working within the ICC to resolve the technical problems described below. Both companies also believe that there are many situations where sRGB is an inappropriate solution. In summary, sRGB provides a simple and broadly applicable, but inflexible color management solution and the ICC provides a robust, flexible color management solution, but with significant overhead.

Table 1 illustrates the guidelines for use of sRGB. It provides a clear model of what ICC profile is used depending on whether ICC profiles are available or not. This model clearly illustrates the complementary nature of sRGB and ICC color management solutions.

Table 1: sRGB ICC Profile Usage in Color Management

ICC/ sRGB	ICC Source Profile	No ICC Source Profile
ICC Destination Profile	ICC Source ICC Destination	sRGB Source ICC Destination
No ICC Destination Profile	ICC Source sRGB Destination	sRGB Source sRGB Destination

Building the Profile

Practical Considerations

The sRGB profile is designed for many different devices including printers, monitors and scanners. It is a generic profile that works well with all of these devices. The profile will be embedded in many images and used for web publication, so it is as small as practical.

The sRGB profile includes information for future compatibility with potential ICC changes and is compatible with the latest CIE recommendations. The profile is compatible with existing color management modules (CMM's) and contains no private tags.

False Starts and Blind Alleys

The ICC profile specification clearly defines how to arrange the bits to create an ICC profile. Originally, it was considered a trivial task to follow the specification and create an sRGB profile. A project to evaluate and test a proposed standard sRGB profile was initiated. This soon became a project to create a profile because of the problems discovered with the test profile. Several attempts to build a better profile failed. These attempts are described to prevent others from rediscovering the same issues and to explain the ICC fixes needed.

A Monitor Profile Implemented with 3D LUTs

The first profile under test was a look-up table (LUT) based input profile with a three dimensional (3D) LUT defining the color transform from Lab to sRGB. This profile was created with a tool that included a gamut compression algorithm. This caused unacceptable results because the transforms were not reversible. Transforming colors with a red, green, or blue value near the lower or upper limit of 0 or 255 produced significant errors with all CMMs tested. The yellow (255,255,0) transform added enough cyan to cause visible and annoying cyan dots on ink jet printers. Multiple passes of an image through color management degraded the colors further. Significant differences in the neutral axis were also observed when using this profile with different CMMs.

XYZ Profile Connection Space

The Lab profile connection space (PCS) requires a non-linear transform to and from sRGB. The XYZ PCS allows a linear transform to be defined if the non-linear gamma adjustment is not included. This transform can be defined as a 3x3 matrix multiply operation. The 3D LUT based profiles have a provision for the definition of a 3x3 matrix for this purpose. The ICC specification clearly defines the order of the data processing of the elements of the tag structure as: (matrix) -> (1d input tables) -> (multidimensional lookup table) -> (1d output tables).

This is the correct order of operations for transforms from the PCS to device space for RGB monitors. Unfortunately, the processing order is the same for transforms back into the PCS, making the 3×3 matrix useless in this direction.

To create a 3×3 matrix multiply operation without an interpolating look up table, a matrix based input profile must be used. This type of profile produces accurate and reversible color conversions with all CMMs tested. Unfortunately, most color management implementations do not allow an input profile to be associated with an output device such as an sRGB printer. This problem requires the ICC to provide a working matrix based solution for printers. This could be solved by extending the monitor matrix based structure for RGB printers, and/or fixing the matrix processing order of the look-up table based structure.

Backward Compatibility

The sRGB profile is expected to be backward compatible with existing color management systems. Although the ICC profile specification provides details on the structure of the file, many technical details and other practical information is missing.

The white point tag is especially confusing. The ICC is aware of the confusing language in this definition.[3] Interpreting the text literally seemed to indicate that the white point value should be D50 to match the profile connection space. However, since the D50 white point of the PCS is included in the header of the profile and there is a precedence established by existing profile creators, the white point is set to that of the sRGB monitor, D65. It is unclear how this tag is used by color management systems.

While testing an existing color management system, it was found that a profile with the existing revision of the ICC spec, 2.10, was ignored by the target CMM and provided no error message. This system required version 2.0 or less. Since the major revision number had not changed, it should have been possible to use a newer profile with an older CMM by disregarding the newer information available in the profile. In addition, this implementation had undocumented restrictions on the size of the 3D LUT. In general, documentation about the restrictions and requirements of color management implementations is unavailable. This makes it impossible to create a profile or profiles that are backward compatible with existing CMMs.

Another practical consideration is the identification of a profile. The three description tags defined in most profiles describe the profile, the manufacturer and the device. Every system uses a different combination of these tags to represent a profile to users. In addition, one system uses the filename. This makes it difficult or impossible for even an informed user to confidently select the correct profile for use.

Profile Interoperability

A robust ICC specification would have enough details that any ICC profile conforming to the specification will work well with any CMM. For example, the interpolation scheme used by the CMM is not standardized. This makes it very difficult to create an LUT based printer profile simulating sRGB. Data values with 0 or 255 are very common in an RGB workflow. When these values are the end points of the look-up table range, they rarely convert without contamination. A work around for this problem required extending then reducing the range of the data using input and output tables so that these values were not on the edge of the data range in the 3D LUT.

Other unanswered questions beg to be addressed by the ICC before interoperable profiles can be built. The exact input value for the look-up tables for a given table size need to be clarified. Are the input values rounded to a whole number before use? Does an odd size 3D LUT guarantee an exact look-up point with no interpolation for the neutral axis? If the 3D LUT is of even size, is there an implied ending grid point and do the grid points represent actual interpolation points or intervals? Does the inclusion of a black point tag imply any black compensation by the CMM? Is the profile used differently if the CMM using it matches the preferred CMM in the header? Is it true that all gamut mapping is defined by the profile and is not the responsibility of the CMM? Exactly what does each rendering intent mean? Is the mathematical or unambiguous description for each rendering intent in order to provide interoperability?

Other Considerations

The fixed D50 profile connection space and lack of compensation for viewing conditions are other limitations. The fixed D50 PCS forces profile makers to choose a chromatic adaptation method for non-D50 devices. Combining profiles with mismatched adaptation methods causes errors in the color transforms. This problem is explained in detail later in this paper.

Viewing conditions make a big difference in the perception of color, but accounting for them is not possible in the ICC workflow. An RGB color space is commonly used for printers even though it is actually a monitor color space. Users expect the color displayed on a monitor to match the color appearance of a printed page. Comparing hard copy to the monitor creates interesting problems.[4] An sRGB monitor has a D65 white point and a D50 ambient white. Partial white adaptation must be considered when comparing a displayed color such as a corporate logo colored with a Pantone color to the Pantone swatch book or a print. Compensation for this effect would require adjusting the data for the perceived white point of the monitor due to partial adaptation but not adjusting the white for the printer. This implies either creating a different sRGB profile for the monitor than the printer or viewing compensation by the CMM. Creating different profiles for every change in the viewing conditions creates profile explosion. Compensation by the CMM is the only practical way to implement this. A color managed work setup that could compensate for the variety of user conditions would significantly improve the ability to match the screen to a print.

The sRGB profile has a viewing conditions tag to allow for future compatibility. Although use of this tag may require an extension of the tag, future CMMs accounting for viewing conditions need to recognize the existing tags as well. As this feature is developed, the units for each field in the tag must be read carefully in the ICC profile specification. A few profiles have been found with viewing condition tags with obvious incorrect units in a few fields. This could be a problem when future color management workflows take advantage of this tag.

Testing the Final Profile

One of the ongoing complaints against color management solutions over the last ten years is that they often simply don't produce good visual matches in real world situations. Some isolated installations and carefully controlled demonstrations have achieved good success, but seldom, if ever, do these reflect real world situations for mass markets. Different software applications display and print unacceptably different colors when reproducing Pantone colors. It is often difficult to get scanners, displays, computers and printers from the same manufacturer to produce acceptable color matches without additional and sophisticated intervention. It is also frequently difficult to get software applications from the same vendor to produce acceptable color matches while interacting with other applications from the same vendor. Finally, it remains unclear where and how color management is performed and what device or software directs this performance in such a way to insure that multiple redundant or conflicting color transformations are not executed. Until this fundamental objection is overcome, it will continue to be difficult to achieve adoption of color management solutions in mass markets.

To even begin to establish testing methods to address situations described above, it is necessary to understand, consider and prioritize the many factors that affect color fidelity. It is common for a particular vendor or product reviewer to try to consider each device or application in isolation. Although this might seem reasonable, it often masks the most difficult problems of integrating the device or application into a real world workflow. Another common solution that can provide very misleading information is summarizing a device's color fidelity with an average

CIELAB delta E* of some particular pictorial image. While this is relevant information, it rarely provides a robust view of the color fidelity issues of an application or device. One of the clear guidelines in establishing color fidelity testing methods is that they reflect and test the multiple software and hardware paths that underlie the most common use cases that end users implement.

It is impractical to test all possible combinations of devices and software. By choosing the most common use cases, applications or devices as reference standards, it becomes practical to establish a stable environment in which to test individual components. Such an environment allows one to test individual applications, CMMs, profiles, devices, and calibration utilities.

A variety of tests were implemented in the actual validation of the “golden standard” sRGB ICC profile. Using a complex document consisting of images, graphics and colored text, over forty different printers were tested using Microsoft Word. These printers represented the top market-share products for both inkjet and electrophotographic printers from the leading device vendors. The sRGB profile was used as both the source and destination profile and compared against print samples on the same printer without color management. It was essential that the color managed path using the same source and destination profile not impose any unacceptable artifacts such as cyan dots on yellow solids, reds turning orange or blues turning purple. Another analysis was performed by mathematically simulating over 1000 Pantone colors through the profile to ensure a minimum delta E was met by inverting the profile. Finally, using a small number calibrated printers, a series of known sRGB values were processed and measured against values known to be a visual match under reference conditions. Portions of these tests were reproduced over different sites and companies.

Contents of the sRGB ICC Profile

The sRGB ICC profile is a matrix profile using the XYZ profile connection space. It identifies itself as a monitor (mntr) profile and is only 3144 bytes.

Matrix profiles are defined with XYZ values of the three colorants, red, green and blue and a tone reproduction curve for each channel. The tone reproduction curve can be defined as a 1D look-up table or a single gamma value. The 3x3 matrix is created by the CMM from the colorant tags. The tone reproduction curve and matrix are inverted by the CMM for reverse transforms.

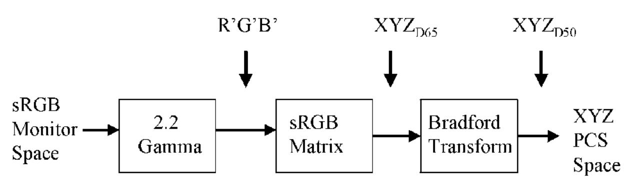

Figure 1. Block diagram of the sRGB profile math

The sRGB specification defines the math for the tone reproduction curve and the contents of a 3x3 matrix transforming sRGB to XYZ at D65. Since the PCS white is D50, the matrix must be adjusted to transform the XYZ values. The chromatic adaptation from D65 to D50 reduces to another 3×3 matrix that is then multiplied with the sRGB matrix to create the final values for the profile. A block diagram of the profile math is shown in Figure 1.

A study of the computational correctness of different chromatic adaptation methods was performed using Pantone colors to create a data set with a large gamut. This study indicated that the Bradford transform[5] is the most reliable, even without the non-linear portion of the transform. This agrees with other visual experiments[6] and the CIE recommended color appearance model.[7] The non-linear adjustment of the Bradford transform can not be included in a 3×3-matrix implementation. The fixed white point conversion from D65 to D50 is implemented by transforming XYZ into cone space with the Bradford matrix, adapting the value from D65 to D50 and then transforming back to XYZ with the inverse Bradford matrix. These steps are shown in Figure 2.

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{D50} = \begin{pmatrix} M_{BFD} \end{pmatrix}^{-1} * \begin{pmatrix} r_{D50}/r_{D65} & 0 & 0 \\ 0 & g_{D50}/g_{D65} & 0 \\ 0 & 0 & b_{D50}/b_{D65} \end{pmatrix} * \begin{pmatrix} M_{BFD} \end{pmatrix} * \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{D65}$$

$r_{D50}, g_{D50}, b_{D50}$ = cone response of D50 White (M_{BFD} * XYZ_{D50})

$r_{D65}, g_{D65}, b_{D65}$ = cone response of D65 White (M_{BFD} * XYZ_{D65})

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{D50} = \begin{pmatrix} 1.0479 & 0.0229 & -0.0502 \\ 0.0296 & 0.9904 & -0.0171 \\ -0.0092 & 0.0151 & 0.7519 \end{pmatrix} * \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{D65}$$

Figure 2. Chromatic adaptation from D65 to D50 using the Bradford matrix.

The final matrix is the product of the reduced Bradford chromatic adaptation matrix and the sRGB matrix. This is shown in Figure 3.

Bradford XYZ_{D65} to XYZ_{D50} sRGB Matrix

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{D50} = \begin{pmatrix} 1.0479 & 0.0229 & -0.0502 \\ 0.0296 & 0.9904 & -0.0171 \\ -0.0092 & 0.0151 & 0.7519 \end{pmatrix} * \begin{pmatrix} .4124 & .3576 & .1805 \\ .2126 & .7152 & .0722 \\ .0193 & .1192 & .9505 \end{pmatrix} * \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

Final Matrix is:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{D50} = \begin{pmatrix} .4361 & .3851 & .1431 \\ .2225 & .7169 & .0606 \\ .0139 & .0971 & .7141 \end{pmatrix} * \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

Figure 3. Final 3 × 3 matrix for the sRGB profile.

The tone reproduction curve is implemented as a 1024 element look-up table to include the small linear region near zero defined in the sRGB specification. A summary of the final profile is shown in Figure 4.

Another factor in transforming into the XYZ PCS space is to account for viewing conditions. It has been previously found that in the sRGB reference conditions the factors of brightness, surround, small area simultaneous contrast (black adaptation) and flare roughly cancel each other out[8]. This results in the CIEXYZ values measured at the face plate of the display being equivalent to the CIEXYZ values after compensation for viewing conditions.

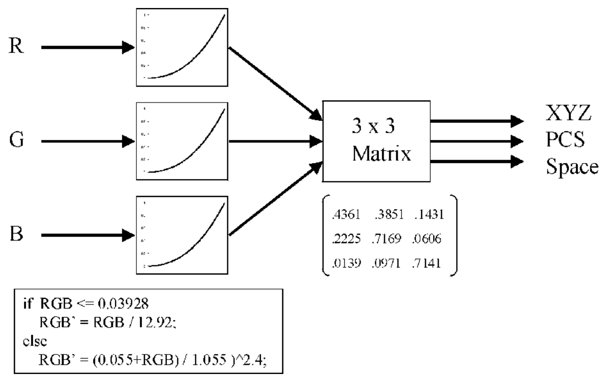

Figure 4. The final sRGB ICC profile

This is the default profile for ICM-2 in Microsoft Windows 98. When the operating system does not have information about a color space, sRGB is assumed and this is the profile used. The profile filename is "sRGB Color Space Profile.icm". Any method of chromatic adaptation besides Bradford will result in a different 3x3 matrix. Although visual experiments show that other methods of adaptation are still good, mixing this profile with another using a different chromatic adaptation method will cause errors in the reversibility and reliability of the color transform.

Other incompatible methods of adjusting the sRGB matrix for the D50 PCS have been observed. One is to use simple scaling between white points, which does the chromatic adaptation in XYZ space rather than cone space. Another has been to ignore the D65 monitor and create the 3x3 matrix using the ITU-R BT.709.2 phosphors and D50 white point directly. Although care was taken to choose a proven chromatic adaptation method, color consistency and accuracy will benefit most by standardizing the chromatic adaptation method.

Recommendations

Any application or color management system desiring an sRGB profile should use the math described in this paper. Where possible the exact sRGB profile should be used. It is freely available on the web site at http://www.srgb.com.

Color management systems need to allow flexibility in associating a profile with a device. Allow the use of a monitor profile for a printer or even a printer profile for a monitor. Universal support and recognition of abstract or color space profiles for any kind of device is also required.

A matrix type profile needs to be available for output devices. This would easily be accomplished if the ICC defined that the current matrix profile structure is valid for all devices and spaces. The use of the 3x3 matrix in the device to PCS multi-function table (3D look-up table) needs to be fixed.

Color management and application vendors could help the community by documenting their interpretation of ICC ambiguities. Better documentation is needed and it should include any restrictions and/or requirements of the ICC profile. The CMM should not preclude the use of a profile with a minor revision newer than the CMM.

The ICC could help the community by publishing guidelines for profile creation and color management implementation. These would clarify the intended use of the header fields. The worn-out-but-still-valid cry for clear definitions of the rendering intents and the white point tag needs an answer. The expectations of the CMM and profile builders for gamut mapping need to be clarified. Other useful guidelines are the exact math, with examples, for determining look-up table input values and how profile builders can improve the integrity of the neutral axis.

A complete solution to the technical problems described requires the work already started in the ICC fix-it and reference implementation work groups. These solutions need to standardize the color adaptation method and appearance model. A method of accounting for viewing conditions is also required. The interpolation method should also be standardized.

Conclusions

Both ICC based color management and sRGB are becoming very visible in today's workflows. They complement each other to provide a complete solution while color management becomes easier and more robust. Application and operating system vendor cooperation, ICC improvements and ICC and CMM documentation are needed to improve the interoperability and accuracy of the increasing color management demands.

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