# Color Accuracy in ICC Color Management System

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## Abstract

ICC committee provides us a standardized profile format and a basic workflow for color transform. However, it is the vendor's responsibility for profile creation and CMM implementation. The color transformation accuracy is determined by both the profile creation and CMM (color management module) implementation. For accurate color transform, ICC profiles that accurately represent the color behavior of color devices or color spaces as well as a CMM that links profiles properly and interpolates colors accurately are required. For the profile creation, we demonstrate huge color differences of color transform due to the change of profile connection spaces (PCS) for a printer ICC profile. We also discuss the color accuracies of color transform for LutType tags with different sizes of 1-D lookup tables (LUT) and different sizes of multi-dimensional LUT. In CMM implementation, we numerically demonstrate the color differences using different linking methods. We also investigate the color differences using different CMMs for color transformation. The results of this research are useful for profile creation and CMM implementation.

## 1. Introduction

ICC color management has been widely accepted in many color imaging software packages and products. However, there is very few publications about its accuracy and interoperability. The concern on accuracy of ICC color management may prevent its widely application.[1] For example, converting an image from one color space to another by Kodak CMS in Windows or Macintosh operating system, the white point may be converted to a color that is slightly off after the conversion, especially when 8-bit LutType data tags are used for the conversion. This makes unacceptable results for printing application in which the white point is usually required to be converted to the paper white exactly. If such an important but simple color cannot be transformed accurately, how can we be confident about the color transform by ICC color management? Without the confidence in the accuracy of ICC color management, users may apply different CMMs for accuracy investigation. This may turn out to be more confusing, because different CMMs give different results and sometimes the differences are very large. It seems that the only way to test the color accuracy is to access the source code of a CMM and to trace into every step of the color conversion. This is the reason that we started writing our own CMM so that we could investigate the CMM accuracy and efficiency and also to study how to write ICC profiles for highest accuracy using a specific CMM.

In this paper, we present some results using different ICC profile formats and different CMMs. The accuracy affected by the ICC profile format is discussed in the section 2. The accuracy affected by CMM linking approaches is discussed in the section 3. The last section is the conclusion remark.

## 2. Accuracy Related to ICC Profile Format

In ICC color management system, the color transformation accuracy is determined by ICC profiles and CMM.[2] In this section, we look at the factors affected the accuracy from the ICC profile format. We only discuss about the format issues related to LUT-based ICC profiles which are always been used for printer profiling. While there are many format issues on LUT type tags, we only focus on the selection of the profile connection space (PCS), sizes of the input and the output 1-D LUTs, and the size of the multidimensional LUT.

### 2.1 Profile Connection Space

The current official PCS color spaces are CIE XYZ and CIE L*a*b*. CIE XYZ color space is not a uniform color space as is CIE L*a*b* color space. In this sense, CIE XYZ color space may not be as good as CIE L*a*b* color space for the color space sampling for linear interpolation, thus it may not be as good as CIE L*a*b* color space serving as PCS for LutType data representation. This is the reason that CIE L*a*b* color space is mostly applied as PCS for printer ICC profiling. However, there are exceptions. CIE XYZ color space can be converted into a monitor RGB color space (without considering nonlinear gamma correction or TRC transformation) linearly by a 3 by 3 matrix multiplication. This kind of linear relationship does not exist in the conversion between CIE L*a*b* and a monitor RGB color space. The close relationship between a monitor RGB color space and the CIE XYZ color space makes it possible to sample monitor RGB gamut surface points in the CIE XYZ grid points of the BToAi tag in a printer profile. Thus those colors in the device gamut surface can be mapped more accurately, and interpolations using [monitor ICC profile] -> PCS -> [printer ICC profile] conversion can be performed more accurately for gamut surface colors and primary colors. Hence, it will be more accurate to convert a monitor's primary colors into a printer's primary colors.[3] Another example is to use XYZ as PCS to create e-sRGB color space ICC profile.[4]

Following is an example showing the difference between using CIE XYZ and L*a*b* as profile connection space to transfer a closed-loop 3-D lookup table for sRGB to printer RGB conversion into an ICC profile. The purpose of this conversion is to use operating systems' resources (e.g. Windows ICM and Mac's ColorSync) or ICC compliant color engines to perform color conversion, and to have the result consistent with that from a closed-loop system.

To create a LUT type based ICC profile, we must first select a PCS. To show the differences using different PCS, both CIE XYZ and L*a*b* PCS were applied to generate ICC profiles. An sRGB color map represents the color transformation from sRGB to printer RGB, while a BtoAi tag table in a printer ICC profile represents the color transformation from XYZ or L*a*b* to printer RGB. A LUT type tag for the conversion from CIE XYZ or L*a*b* color space to printer device color space maps a much larger color gamut into the same printer device color space than a closed-loop LUT does. To construct BToAi tag data using CIE XYZ or L*a*b* PCS, we have to start from a gamut larger than sRGB gamut. In order to preserve the color reproduction consistency of the closed-loop flow and the ICC flow, tag data with grid points inside the RGB gamut are interpolated using the RGB LUT; and grid points outside the RGB gamut are mapped into the RGB gamut first then mapped to the printer device space by interpolating the RGB LUT. Because the RGB LUT was applied for colors inside the RGB gamut, different gamut mapping techniques affect boundary colors and some near-boundary colors only.

The sRGB color map we created is a 17x17x17 LUT. For a BToAi tag with L*a*b* PCS, the input and the output 1-D LUTs are set to identity, and the 3x3 matrix is also identity. The L*a*b* LUT grid points that are out of sRGB gamut are mapped to sRGB gamut, and then 3-D interpolated to printer RGB. For a BToAi tag with XYZ PCS, the 3x3 matrix is applied to convert XYZ into linear sRGB, the input 1-D LUTs convert linear sRGB values into nonlinear sRGB values. Thus, the 3-D LUT of the BToAi tag is essentially for sRGB to printer RGB conversion, which is exactly the same as the closed-loop sRGB color map does. Hence, the closed-loop 3-D LUT is copied to the BToAi tag (linear interpolation is performed if the LUT sizes are different or the grid points are different). The output 1-D LUT is set to identity.

Several CMMs were tested for the color conversion. The result using the ICC profile with L*a*b* PCS is out of expectation. The color conversion of a yellow color ramp as an example is shown in Table 1. The first column is a set of the input sRGB triplets for the yellow ramp. The second column lists the corresponding printer RGB triplets from the original closed-loop 3-D LUT. The transform from the input sRGB to printer RGB by Photoshop built-in CMM (Adobe Photoshop 5.5 in Windows 2000) is shown in the third column. The transform by Kodak CMS (Photoshop 5.5 in Windows 2000) is shown in the fourth column. The transform by Heidelberg CMM (Photoshop 5.0 in Macintosh) is shown in the last column. The color conversion from none of the three CMMs reproduces the pure yellow as the closed-loop LUT does, and the highly saturated yellows are desaturated.

Creating a 3-D sRGB to printer RGB LUT using sRGB color space profile and the printer ICC profile with L*a*b* PCS, we found that 3-D LUTs converted from ICC profiles are very closed to the original 3-D LUT except for those points in the sRGB gamut surface. The problems for RGB gamut surface colors are: pure input colors (e.g. pure magenta and yellow) are not converted to pure output colors; saturated colors (e.g. 100% red, green, blue, cyan, magenta, and yellow) are desaturated; and hues shift for some gamut surface colors. The reason of the distortion is explained in the reference.[3]

We also constructed a printer ICC profile using CIE XYZ PCS for this closed-loop 3-D LUT. The color conversion of the same yellow ramp is shown in Table 2. The conversion by Photoshop built-in CMM and Heidelberg CMM produce almost the same result as the original closed-loop LUT does. However, the Kodak CMS produces very different result: the converted yellows are not pure and the highly saturated yellows are desaturated.

**Table 1. The mapping from sRGB to printer RGB for the yellow ramp applying a printer ICC profile created with L*a*b* PCS**

| Input sRGB | Printer RGB: Original 3-D LUT | Printer RGB: Adobe Built-in CMM | Printer RGB: Kodak CMM | Printer RGB: Heidelberg CMM |
|---|---|---|---|---|
| 255 255 0 | 255 255 0 | 254 255 33 | 254 255 32 | 254 255 32 |
| 255 255 16 | 255 255 28 | 254 255 38 | 254 255 37 | 254 255 38 |
| 255 255 32 | 255 255 54 | 254 255 47 | 254 255 45 | 254 255 47 |
| 255 255 48 | 255 255 76 | 253 255 60 | 254 255 59 | 254 255 60 |
| 255 255 64 | 255 255 93 | 253 255 77 | 254 255 76 | 253 255 77 |
| 255 255 80 | 255 255 108 | 253 255 96 | 254 255 95 | 253 255 96 |
| 255 255 96 | 255 255 125 | 253 255 114 | 253 255 113 | 253 255 114 |
| 255 255 112 | 255 255 144 | 253 255 134 | 253 255 133 | 253 255 134 |
| 255 255 128 | 255 255 161 | 252 255 155 | 253 255 154 | 252 255 155 |
| 255 255 144 | 255 255 177 | 252 255 173 | 253 255 173 | 252 255 173 |
| 255 255 160 | 255 255 190 | 253 255 188 | 254 255 188 | 253 255 188 |
| 255 255 176 | 255 255 202 | 253 255 201 | 254 255 202 | 253 255 201 |
| 255 255 192 | 255 255 214 | 254 255 213 | 254 255 214 | 254 255 213 |
| 255 255 208 | 255 255 223 | 253 255 224 | 253 255 224 | 253 255 224 |
| 255 255 224 | 255 255 233 | 251 255 234 | 252 255 234 | 251 255 234 |
| 255 255 240 | 255 255 243 | 252 255 244 | 253 255 245 | 252 255 244 |
| 255 255 255 | 255 255 255 | 255 255 255 | 255 255 255 | 255 255 255 |

**Table 2. The mapping from sRGB to printer RGB for the yellow ramp using a printer ICC profile with XYZ PCS**

| Input sRGB | | | Printer RGB | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Original 3-D LUT | | | Adobe Built-in CMM | | | Kodak CMM | | | Heidelberg CMM | | |
| 255 | 255 | 0 | 255 | 255 | 0 | 255 | 255 | 0 | 246 | 255 | 68 | 255 | 255 | 0 |
| 255 | 255 | 16 | 255 | 255 | 28 | 255 | 255 | 28 | 246 | 255 | 70 | 255 | 255 | 28 |
| 255 | 255 | 32 | 255 | 255 | 54 | 255 | 255 | 54 | 246 | 255 | 74 | 255 | 255 | 54 |
| 255 | 255 | 48 | 255 | 255 | 76 | 255 | 255 | 76 | 246 | 255 | 80 | 255 | 255 | 76 |
| 255 | 255 | 64 | 255 | 255 | 93 | 255 | 255 | 93 | 246 | 255 | 88 | 255 | 255 | 93 |
| 255 | 255 | 80 | 255 | 255 | 108 | 255 | 255 | 108 | 246 | 255 | 100 | 255 | 255 | 108 |
| 255 | 255 | 96 | 255 | 255 | 125 | 255 | 255 | 125 | 245 | 255 | 116 | 255 | 255 | 125 |
| 255 | 255 | 112 | 255 | 255 | 144 | 255 | 255 | 144 | 245 | 255 | 133 | 255 | 255 | 144 |
| 255 | 255 | 128 | 255 | 255 | 161 | 255 | 255 | 161 | 245 | 255 | 152 | 255 | 255 | 161 |
| 255 | 255 | 144 | 255 | 255 | 177 | 255 | 255 | 177 | 245 | 255 | 170 | 255 | 255 | 178 |
| 255 | 255 | 160 | 255 | 255 | 190 | 255 | 255 | 190 | 246 | 255 | 189 | 255 | 255 | 191 |
| 255 | 255 | 176 | 255 | 255 | 202 | 255 | 255 | 202 | 246 | 255 | 204 | 255 | 255 | 203 |
| 255 | 255 | 192 | 255 | 255 | 214 | 255 | 255 | 214 | 247 | 255 | 214 | 255 | 255 | 215 |
| 255 | 255 | 208 | 255 | 255 | 223 | 255 | 255 | 223 | 248 | 255 | 225 | 255 | 255 | 224 |
| 255 | 255 | 224 | 255 | 255 | 233 | 255 | 255 | 233 | 250 | 255 | 235 | 255 | 255 | 234 |
| 255 | 255 | 240 | 255 | 255 | 243 | 255 | 255 | 243 | 253 | 255 | 245 | 255 | 255 | 244 |
| 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 |

Comparing Table 1 with Table 2, we can see that applying XYZ PCS comes out with higher color accuracy in this specific application. This is because we can convert XYZ into sRGB linearly with the aid of 1-D LUTs. Thus the 3-D interpolation is performed in sRGB to printer RGB which is exactly the same as the 3-D closed-loop LUT does. Because the primary matching is preserved, this method can be applied for primary matching for the saturation rendering intent. This example shows a method to convert a monitor's primary colors into a printer's primary colors accurately by ICC color management system. It also shows that choosing different PCS for ICC profiling may come out very different results.

## 2.2 Sizes of Input and Output 1-D LUTs and the Multidimensional LUT

The formats of different LUT types (Lut8Type/ Lut16Type and LutBToAType/LutAToBType) are similar. All of them allow a set of 1-D LUTs in front of the multi-dimensional LUT and a set of 1-D LUTs following the multi dimensional LUT. These 1-D LUTs are used to extract the noninterdependent nonlinear factors of the input and the output color spaces. Because linear interpolation methods are used for real-time multidimensional interpolation in CMM implementations, any nonlinear relationship between two grid points is approximated by linear transform therefore interpolation error is unavoidable. If the input and/or the output color spaces are very nonlinear, applying input and output 1-D LUTs generally increases the color conversion accuracy. Because 8-bit 1-D LUTs are used in the Lut8Type, this may not be accurate enough for non-linear transform. To utilize 1-D LUTs accurately, Lut16-Type or LutBToAType/LutAToBType should be used. To investigate the differences of building ICC profiles using nonlinear 1-D LUTs and using identical 1-D LUTs, we created e-sRGB ICC profiles using different 1-D LUTs and used them with different CMMs for color transform.[4] First, we created a 16-bit e-sRGB ICC profile using the Lut16Type and XYZ PCS, and the input and the output 1-D LUTs are set to identity. To test the accuracy, we converted colors from sRGB to e-sRGB and then back to sRGB, then compared the difference between the input sRGB and the output sRGB. Photoshop's Profile-to-Profile transform was used for the conversion. For Adobe built-in CMM and Kodak CMM, Photoshop version 5.5 in Windows 2000 was used. For Heidelberg CMM, Photoshop version 5.0 in Macintosh was used. Because 8-bit/channel is not accurate to represent e-sRGB color space, we performed following sequences of transforms for sRGB to sRGB conversion: 8-bit sRGB $\rightarrow$ 16-bit sRGB $\rightarrow$ 16-bit e-sRGB $\rightarrow$ 16-bit sRGB $\rightarrow$ 8-bit sRGB.

Table 3 shows the color conversion results for the yellow and the gray ramps. The upper half colors are pure yellow, and the bottom half colors are neutral gray. It shows that the output color values are very different from the input color values if the color values are small. This is the result of large errors in the linear 3-D interpolation due to very nonlinear characteristics in the low digital value region. The yellow ramp shows that the error is in a channel with low digital counts and it is not propagated to other channels. This gives us a hint that using 1-D LUTs for nonlinear transform and using the multi-dimensional LUT for linear interpolation may reduce the interpolation error. To prove this, we built another e-sRGB ICC profile with non-linear 1-D LUTs.[4] The conversion between the nonlinear e-sRGB to linear e-sRGB is performed in the 1-D LUTs, and the conversion between the linear e-sRGB and CIE XYZ is performed in the 3-D LUT. To make a proper ICC version-2 profile (formatted with the ICC profile specification 3.x), we must shift color values in 1-D LUTs so that they are nonnegative, and shift them back in the 3-D LUT. The color conversion results from the e-sRGB profile with 1024-entry nonlinear 1-D LUTs for the yellow ramp and the neutral gray ramp are shown in Table 4. With this e-sRGB profile, any sRGB color is converted back to exactly the same color by Photoshop built-in CMM and Heidelberg CMM. This proves that using 1-D LUTs properly improves the interpolation accuracy dramatically. The result also shows that Kodak CMM is not as accurate as the other two for the color transform using this type of ICC profiles. Reducing the nonlinear 1-D LUTs to 256-entry, the results are shown in Table 5. The errors in the low digital count region show that the 256-entry 1-D table size is not large enough to represent the nonlinear characteristics.

**Table 3. Conversion from sRGB → e-sRGB → sRGB using an e-sRGB ICC profile with identity 1-D LUTs in the Lut16Type tag**

| Input sRGB | | | Output sRGB | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Kodak CMM | | | Adobe CMM | | | Heidelberg CMM | | |
| 255 | 255 | 0 | 255 | 255 | 7 | 255 | 255 | 14 | 255 | 255 | 14 |
| 255 | 255 | 16 | 255 | 255 | 18 | 255 | 255 | 21 | 255 | 255 | 21 |
| 255 | 255 | 32 | 255 | 255 | 31 | 255 | 255 | 32 | 255 | 255 | 32 |
| 255 | 255 | 48 | 255 | 255 | 44 | 255 | 255 | 45 | 255 | 255 | 45 |
| 255 | 255 | 64 | 255 | 255 | 59 | 255 | 255 | 58 | 255 | 255 | 58 |
| 255 | 255 | 80 | 255 | 255 | 77 | 255 | 255 | 76 | 255 | 255 | 76 |
| 255 | 255 | 96 | 255 | 255 | 96 | 255 | 255 | 96 | 255 | 255 | 95 |
| 255 | 255 | 112 | 255 | 255 | 112 | 255 | 255 | 111 | 255 | 255 | 111 |
| 255 | 255 | 128 | 255 | 255 | 129 | 255 | 255 | 128 | 255 | 255 | 128 |
| 255 | 255 | 144 | 255 | 255 | 145 | 255 | 255 | 144 | 255 | 255 | 144 |
| 255 | 255 | 160 | 255 | 255 | 161 | 255 | 255 | 160 | 255 | 255 | 160 |
| 255 | 255 | 176 | 255 | 255 | 177 | 255 | 255 | 176 | 255 | 255 | 176 |
| 255 | 255 | 192 | 255 | 255 | 193 | 255 | 255 | 192 | 255 | 255 | 192 |
| 255 | 255 | 208 | 255 | 255 | 210 | 255 | 255 | 208 | 255 | 255 | 208 |
| 255 | 255 | 224 | 255 | 255 | 226 | 255 | 255 | 224 | 255 | 255 | 224 |
| 255 | 255 | 240 | 255 | 255 | 242 | 255 | 255 | 240 | 255 | 255 | 240 |
| 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16 | 16 | 16 | 0 | 5 | 5 | 6 | 6 | 5 | 0 | 3 | 5 |
| 32 | 32 | 32 | 2 | 10 | 12 | 16 | 16 | 14 | 3 | 11 | 13 |
| 48 | 48 | 48 | 18 | 26 | 27 | 32 | 34 | 29 | 16 | 25 | 27 |
| 64 | 64 | 64 | 48 | 55 | 50 | 56 | 58 | 50 | 48 | 53 | 48 |
| 80 | 80 | 80 | 58 | 72 | 81 | 75 | 79 | 80 | 58 | 70 | 79 |
| 96 | 96 | 96 | 79 | 92 | 95 | 90 | 95 | 94 | 78 | 91 | 94 |
| 112 | 112 | 112 | 102 | 111 | 112 | 109 | 111 | 112 | 101 | 109 | 112 |
| 128 | 128 | 128 | 125 | 128 | 129 | 126 | 127 | 128 | 124 | 126 | 128 |
| 144 | 144 | 144 | 144 | 144 | 145 | 143 | 144 | 144 | 142 | 143 | 144 |
| 160 | 160 | 160 | 160 | 161 | 161 | 159 | 160 | 160 | 158 | 159 | 160 |
| 176 | 176 | 176 | 176 | 177 | 177 | 175 | 176 | 176 | 175 | 176 | 176 |
| 192 | 192 | 192 | 193 | 193 | 194 | 192 | 192 | 192 | 192 | 193 | 193 |
| 208 | 208 | 208 | 209 | 210 | 210 | 208 | 208 | 208 | 207 | 208 | 208 |
| 224 | 224 | 224 | 225 | 226 | 226 | 224 | 224 | 224 | 223 | 224 | 224 |
| 240 | 240 | 240 | 241 | 242 | 242 | 240 | 240 | 240 | 240 | 240 | 240 |
| 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 |

**Table 4. Conversion from sRGB → e-sRGB → sRGB using an e-sRGB ICC profile with nonlinear 1024-entry 1-D LUTs in the Lut16Type tag**

| Input sRGB | | | Output sRGB | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Kodak CMM | | | Adobe CMM | | | Heidelberg CMM | | |
| 255 | 255 | 0 | 255 | 255 | 0 | 255 | 255 | 0 | 255 | 255 | 0 |
| 255 | 255 | 16 | 255 | 255 | 18 | 255 | 255 | 16 | 255 | 255 | 16 |
| 255 | 255 | 32 | 255 | 255 | 32 | 255 | 255 | 32 | 255 | 255 | 32 |
| 255 | 255 | 48 | 255 | 255 | 48 | 255 | 255 | 48 | 255 | 255 | 48 |
| 255 | 255 | 64 | 255 | 255 | 65 | 255 | 255 | 64 | 255 | 255 | 64 |
| 255 | 255 | 80 | 255 | 255 | 81 | 255 | 255 | 80 | 255 | 255 | 80 |
| 255 | 255 | 96 | 255 | 255 | 97 | 255 | 255 | 96 | 255 | 255 | 96 |
| 255 | 255 | 112 | 255 | 255 | 113 | 255 | 255 | 112 | 255 | 255 | 112 |
| 255 | 255 | 128 | 255 | 255 | 129 | 255 | 255 | 128 | 255 | 255 | 128 |
| 255 | 255 | 144 | 255 | 255 | 145 | 255 | 255 | 144 | 255 | 255 | 144 |
| 255 | 255 | 160 | 255 | 255 | 161 | 255 | 255 | 160 | 255 | 255 | 160 |
| 255 | 255 | 176 | 255 | 255 | 177 | 255 | 255 | 176 | 255 | 255 | 176 |
| 255 | 255 | 192 | 255 | 255 | 193 | 255 | 255 | 192 | 255 | 255 | 192 |
| 255 | 255 | 208 | 255 | 255 | 209 | 255 | 255 | 208 | 255 | 255 | 208 |
| 255 | 255 | 224 | 255 | 255 | 226 | 255 | 255 | 224 | 255 | 255 | 224 |
| 255 | 255 | 240 | 255 | 255 | 242 | 255 | 255 | 240 | 255 | 255 | 240 |
| 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16 | 16 | 16 | 19 | 16 | 14 | 16 | 16 | 16 | 16 | 16 | 16 |
| 32 | 32 | 32 | 32 | 32 | 31 | 32 | 32 | 32 | 32 | 32 | 32 |
| 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 |
| 64 | 64 | 64 | 64 | 65 | 65 | 64 | 64 | 64 | 64 | 64 | 64 |
| 80 | 80 | 80 | 80 | 82 | 81 | 80 | 80 | 80 | 80 | 80 | 80 |
| 96 | 96 | 96 | 97 | 98 | 97 | 96 | 96 | 96 | 96 | 96 | 96 |
| 112 | 112 | 112 | 113 | 113 | 113 | 112 | 112 | 112 | 112 | 112 | 112 |
| 128 | 128 | 128 | 129 | 129 | 129 | 128 | 128 | 128 | 128 | 128 | 128 |
| 144 | 144 | 144 | 146 | 145 | 145 | 144 | 144 | 144 | 144 | 144 | 144 |
| 160 | 160 | 160 | 161 | 161 | 161 | 160 | 160 | 160 | 160 | 160 | 160 |
| 176 | 176 | 176 | 177 | 177 | 177 | 176 | 176 | 176 | 176 | 176 | 176 |
| 192 | 192 | 192 | 193 | 193 | 193 | 192 | 192 | 192 | 192 | 192 | 192 |
| 208 | 208 | 208 | 210 | 209 | 210 | 208 | 208 | 208 | 208 | 208 | 208 |
| 224 | 224 | 224 | 226 | 225 | 226 | 224 | 224 | 224 | 224 | 224 | 224 |
| 240 | 240 | 240 | 242 | 242 | 242 | 240 | 240 | 240 | 240 | 240 | 240 |
| 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 |

The impact of the size of the multi-dimensional LUT can be easily found in printer ICC profiling. The difference of using different sizes of the multi-dimensional LUT can be detected visually from printed hardcopies in printer color calibration. Because many nonlinear channel interdependent factors existed in printer color calibration, the larger the size of 3-D LUT for BToAi tag, the higher the accuracy can be achieved. A 32x32x32 or 33x33x33 LUT is often used for BToAi tag. A 16x16x16 or 17x17x17 LUT may be acceptable. However, if the LUT size is reduced to 9x9x9, banding (or quantization) artifact will probably show up in neutral gray ramps, and highly saturated colors (colors closed to gamut surface) will be desaturated.

## 3. Accuracies Related to CMM Implementation

A CMM links a set of profiles and usually merges them to a simple object for fast color transform. Different linking approaches and different interpolation methods (e.g. tetrahedral and trilinear interpolations) result in different outputs. Tables 1 to 5 have shown different color conversion results transformed through different CMMs in which different linking and interpolation approaches may be implemented. There are two basic linking approaches to link a set of ICC profiles. One is to merge them into a single multi-dimensional LUT, and the other is to merge them into a deviceLink profile which includes a set of input 1-D

LUTs, a multi-dimensional LUT, and a set of output 1-D LUTs. The color conversion by the first approach is faster than that by the second approach. However, the second approach may come up with more accurate color transformation. Table 6 shows the sRGB to printer CMYK conversion using a printer ICC profile in which the CMYK linearization curves are put into the output 1-D LUTs of the BToAi tag. The first column is the input sRGB neutral gray ramp. The next two columns are the corresponding CMYK values converted by two linking approaches with the author's CMM. In the second column, a 17x17x17 LUT is created for sRGB to CMYK interpolation during the linking, and 8-bit tetrahedral interpolation is performed. In the last column, the input 1-D LUT of the source profile is preserved and the 1-D output LUT of the BToAi tag of the printer profile is also preserved. Thus, the color transform becomes a 1-D lookup, 3-D interpolation, and 1-D lookup sequential processing. Because the input 1-D LUT is an inverse 2.2 gamma LUT for sRGB to linear sRGB conversion, and the output 1-D LUT is also nonlinear (see Fig. 1), the 3-D interpolation is performed in linear sRGB to linearized CMYK instead of non-linear sRGB to non-linear CMYK. This makes the output CMYK values very different from those by the one-step 3-D interpolation. Now the question is which is more accurate. In general, the 1-D → 3-D → 1-D transform is more accurate than that with a onestep 3-D interpolation. However, the 1-D LUTs must have higher bit-depth than the requested output bit-depth to guarantee the accuracy. For example, if the output bit-depth is 8-bit, the bit-depth of 1-D LUTs should be more than 8-bit. So does the interpolation in the middle step. For the conversion from a monitor RGB color space to the printer CMYK color space, applying input 1-D LUTs may degrade the accuracy. This is because the input nonlinear RGB color space is visually more uniform than the linear RGB color space. By converting the input RGB to linear RGB using input 1-D LUTs, the grid points for the 3-D interpolation becomes visually less uniform. This may result in more color error for the RGB to CMYK transform. Hence, for accurate transformation from a monitor RGB color space to a printer CMYK color space, we should only keep the output 1-D LUTs and merge the input 1-D LUT with the 3-D LUT. Generating a larger multi-dimensional LUT also guarantees higher interpolation accuracy.

**Table 5. Conversion from sRGB → e-sRGB → sRGB using an e-sRGB ICC profile with nonlinear 256-entry 1-D LUTs in the Lut16Type tag**

| Input sRGB | | | Output sRGB | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Kodak CMM | | | Adobe CMM | | |
| 0 | 0 | 0 | 2 | 2 | 2 | 0 | 0 | 0 |
| 16 | 16 | 16 | 18 | 14 | 14 | 14 | 14 | 14 |
| 32 | 32 | 32 | 32 | 32 | 32 | 32 | 32 | 32 |
| 48 | 48 | 48 | 48 | 49 | 48 | 48 | 48 | 48 |
| 64 | 64 | 64 | 64 | 66 | 65 | 64 | 64 | 64 |
| 80 | 80 | 80 | 80 | 82 | 81 | 80 | 80 | 80 |
| 96 | 96 | 96 | 96 | 98 | 97 | 96 | 96 | 96 |
| 112 | 112 | 112 | 113 | 114 | 113 | 112 | 112 | 112 |
| 128 | 128 | 128 | 129 | 130 | 129 | 128 | 128 | 128 |
| 144 | 144 | 144 | 146 | 145 | 145 | 144 | 144 | 144 |
| 160 | 160 | 160 | 161 | 162 | 161 | 160 | 160 | 160 |
| 176 | 176 | 176 | 178 | 178 | 177 | 176 | 176 | 176 |
| 192 | 192 | 192 | 194 | 194 | 194 | 192 | 192 | 192 |
| 208 | 208 | 208 | 210 | 210 | 210 | 208 | 208 | 208 |
| 224 | 224 | 224 | 226 | 226 | 226 | 224 | 224 | 224 |
| 240 | 240 | 240 | 242 | 242 | 242 | 240 | 240 | 240 |
| 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 |

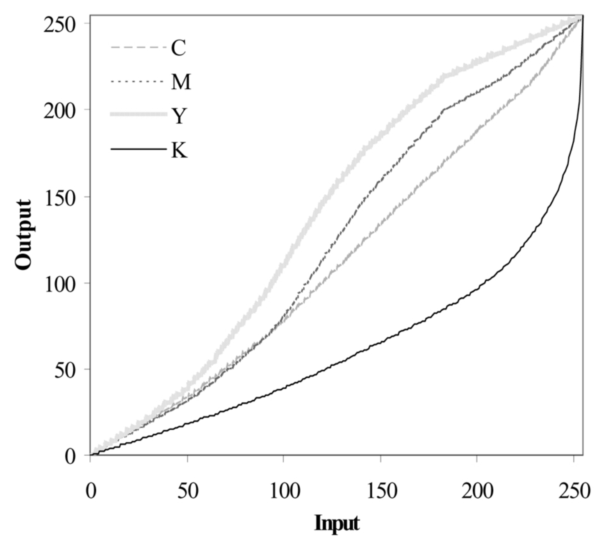


*Fig.1 The output 1-D LUTs of the BToAi tag in the printer ICC profile used in this experiment*

**Table 6. sRGB to CMYK conversion with two different linking processes**

| SRGB | | | create a 3D object | | | | create a 1D->3D->1D object | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| R | G | B | C | M | Y | K | C | M | Y | K |
| 0 | 0 | 0 | 108 | 125 | 156 | 255 | 108 | 125 | 156 | 255 |
| 16 | 16 | 16 | 115 | 104 | 137 | 90 | 106 | 121 | 152 | 147 |
| 32 | 32 | 32 | 98 | 90 | 121 | 54 | 101 | 113 | 145 | 105 |
| 48 | 48 | 48 | 90 | 86 | 113 | 38 | 94 | 101 | 131 | 73 |
| 64 | 64 | 64 | 82 | 79 | 103 | 27 | 83 | 83 | 110 | 37 |
| 80 | 80 | 80 | 73 | 70 | 94 | 18 | 74 | 71 | 93 | 18 |
| 96 | 96 | 96 | 66 | 64 | 83 | 11 | 66 | 64 | 83 | 11 |
| 112 | 112 | 112 | 59 | 56 | 73 | 6 | 59 | 56 | 72 | 6 |
| 128 | 128 | 128 | 51 | 48 | 61 | 2 | 51 | 48 | 60 | 3 |
| 144 | 144 | 144 | 41 | 38 | 47 | 0 | 42 | 39 | 48 | 1 |
| 160 | 160 | 160 | 33 | 31 | 37 | 0 | 34 | 31 | 37 | 0 |
| 176 | 176 | 176 | 25 | 24 | 28 | 0 | 26 | 25 | 29 | 0 |
| 192 | 192 | 192 | 19 | 18 | 20 | 0 | 20 | 18 | 21 | 0 |
| 208 | 208 | 208 | 12 | 12 | 13 | 0 | 13 | 13 | 14 | 0 |
| 224 | 224 | 224 | 7 | 7 | 8 | 0 | 7 | 7 | 8 | 0 |
| 240 | 240 | 240 | 2 | 2 | 3 | 0 | 3 | 3 | 3 | 0 |
| 255 | 255 | 255 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

## 4. Conclusions

For accurate color transformation in ICC color management system, ICC profiles must be properly formatted and CMM must be implemented correctly. The PCS selection may be very critical for accurate color representation for some applications. We numerically demonstrated the differences of representing a Lut8/Lut16Type tag using both XYZ PCS and L*a*b* PCS. CIE L*a*b* color space, as a uniform color space, is generally a more suitable PCS for printer ICC profiling. However, if a device color space can be linearly transform to CIE XYZ color space by a matrix and 1-D LUTs, CIE XYZ may be a more suitable PCS for accurate color transform. One example of this application is to create printer ICC profile for primary preservation for a monitor RGB color space to CMYK color space transformation. Another place that can potentially improve the color accuracy of color representation is to use the input and the output 1-D LUTs properly. For device profiling, the accuracy can be improved if each device plane is linearized and put the linearized curves in the 1-D LUTs of the Lut8Type/Lut16Type or LutBToAType/LutAToBTye tags. If the 1-D curves are very nonlinear, large 1-D LUTs should be generated for accurate representation. There are two basic linking approaches for CMM implementation, creating a multi-dimensional LUT for fast interpolation or creating an [1-D LUTs → multi-dimensional LUT → 1-D LUTs] object for more accurate transformation. The improvement on the accuracy of the later approach depends on how the input 1-D LUTs and the output 1-D LUTs do. If the input 1-D LUTs transform colors so that the multi-dimensional interpolation performs in a more linear space or the grid points of the multi-dimensional LUT are visually more uniform, keeping the input 1-D LUTs should improve the accuracy. Otherwise, the accuracy may be degraded. One example is the color transform from sRGB to printer CMYK space. If keeping the input 1-D LUTs to transform nonlinear sRGB values into linear sRGB values, the accuracy may be degraded. This is because the nonlinear sRGB color space is visually more uniform than the linear sRGB color space. For the color transform from a color space to printer CMYK space, keeping the output 1-D LUTs (linearization LUT for each of CMYK planes) generally improves the interpolation accuracy. In any linking approaches, creating a reasonably large multi-dimensional LUT always guarantees the transform accuracy.

## References


1. D. Margulis and C. Murrphy, “Color Management for the Pragmatic: Where Do We Go From Here”, Seybold Report: Analyzing Publishing Technologies, April 16, 2001.
2. Specification ICC.1:1998-09 File Format for Color Profiles, http://www.color.org/.
3. H. Zeng, “Primary Preservation in ICC Color Management System”, Proc. SPIE: Color Imaging: Device-Independent Color, Color Hardcopy, and Graphic Arts VII, (2002).
4. H. Zeng and M. Nielsen, “Color Transformation Accuracy and Efficiency in ICC Color Management”, Proc. IS&T/SIC 9th Color Imaging Conf., 224-232 (2001).