Retaining Color Fidelity in Photo CD Image Migration

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Abstract

The Photo CD system, originally aimed at consumers, has also been used by cultural institutions to store digital images from scanned photographic film, prints, and documents. With improvements in technology and anticipated adoption of new digital image standards, e.g., JPEG 2000, retention of image fidelity during migration of digital collections is often a concern. In a previous report (Archiving Conf. 2005), we described the format and colorimetric definition of images stored on Photo CD disks. Here we address several steps that can be taken to ensure the retention of the original subject color information, and the straightforward display and exchange of derivative images. The rationale and practical considerations for using embedded ICC color profiles will also be discussed.

Introduction

The Photo CD system was developed to support the capture and display of images from a wide variety of imaging media and devices. This was accomplished using a unique color-encoding and image file format. Originally aimed at consumers and professional photographers, the system was also used by cultural institutions to store images from scanned material.[1] With the development of, and migration to, new digital imaging standards, retention of both spatial and color image fidelity is of concern to many institutions.[2] In this paper we address several steps that can be taken for successful reformatting. Our focus is on the retention of color fidelity during image migration.

The Photo CD color-encoding specification, which is consistent with color standards for imaging devices, was designed to provide high-quality images on color displays without requiring special adjustments or extensive image processing. The Kodak Photo CD Image Pac file format[3] involves storing the digital image at several sampling resolutions. This facilitates image viewing and printing using a wide range of devices. The Image Pac elements for about 100 digital images are stored on a single Photo CD compact disk.

Kodak PhotoYCC Color-Encoding Specification

The PhotoYCC color-encoding specification[4] is used to express the original-subject colorimetry in terms of RGB exposure factor values. These values represent those that would have been produced by a specified reference image-capture device, had it captured the same subject, illuminated by CIE Standard Illuminant D_{65}. The defined red, green, and blue spectral responsivities of the reference image-capture device were chosen to be equivalent to the color-matching functions corresponding to the reference primaries specified for ITU Recommendation ITU-R BT.709. Signal values from practical video cameras that conform to this standard produce all-positive signals. However, because the reference capture device is defined by its theoretical characteristics, it can form negative signal values. The PhotoYCC specification accommodates this situation, which corresponds to the capture of original-subject color information outside the color gamut of a video display.

In addition to this extended color-gamut, the PhotoYCC color-encoding specification deals with the extensive range of luminance information encountered in much original-subject matter and captured by input photographic media. This includes specular highlights and image areas more highly illuminated than the main subject. The color encoding accommodates luminance-factor values up to two times that produced by a perfect white reflector in the principal subject area.

In summary, PhotoYCC-encoded image data represent original-subject color image information in a way that accommodates a wide range of scene exposures and allows rapid display of high-quality photographic images. A way to preserve this input-referred color information, extended dynamic range, and color gamut, is to migrate to the Reference Input Medium Metric (RIMM)[5] color space. Before discussing recommendations for such a migration, we review the color transformation equations that define the relationship between stored PhotoYCC image data values and the RIMM RGB (tristimulus) values.

Objectives for Conversion

A color encoding for conversion of Photo CD image files amenable to objectives for archiving and preservation should ideally retain the salient original-subject nature and extensive color gamut and luminance dynamic range characteristics of the extant image files. Additionally, such a conversion should allow for straightforward production of appropriately rendered images in a variety of modalities without imposing any loss of color information to the converted image data. Moreover, it would be convenient if such a conversion could be accomplished using an existing color-management infrastructure.

Eastman Kodak Company developed the RIMM RGB color encoding to be used with digital images expressed in an unrendered, or scene-referred, image state. As with PhotoYCC, the RIMM encoding provides a color gamut encompassing virtually all real-world surface colors encountered in typical imaging applications and supports a luminance range sufficient to include critical specular-highlight information. RIMM is also well suited as an input space to the ICC profile connection space (PCS), both of which have identically defined adaptive white point chromaticities. RIMM RGB is applicable for numerous imaging functions including the archiving and interchanging of unrendered-state images. The 8-bit version of this color encoding is particularly well suited for conversions of legacy PhotoYCC images with minimal loss.

Definition of RIMM RGB Color Encoding

The reference viewing conditions associated with RIMM RGB are consistent with those of typical original subject matter viewing environments

- Luminance level >1,600 cd/m^2
- Average image surround (i.e., area surrounding the scene is similar in luminance and chromaticity to that of the overall scene)
- No viewing flare
- Adaptive white-point chromaticities corresponding to those of CIE Standard Illuminant D_{50} (x = 0.3457, y = 0.3585)

RIMM RGB color values are expressed in terms of flareless colorimetric measurements referenced to a set of RGB primaries capable of expressing virtually all real-world surface colors using all-positive exposure-factor values. The reference primaries and the white produced by their additive combination are defined by their CIE *x, y* chromaticity values given in Table 1.

Table 1: RIMM RGB reference primaries and white point chromaticities

Color	*x*	*y*
Red	0.7347	0.2653
Green	0.1596	0.8404
Blue	0.0366	0.0001
White	0.3457	0.3585

General Architecture for Conversion

The architecture shown in Fig. 1 accomplishes these objectives within an ICC-based color-management framework. The required color-signal processing is embodied in two distinct types of profiles. The first step (unpack) involves the assembly of the multiresolution pyramid elements of each digital image into a single image array. This would usually result in a 2048 lines × 3072 pixels × 3 colors array for 16Base Photo CD image.

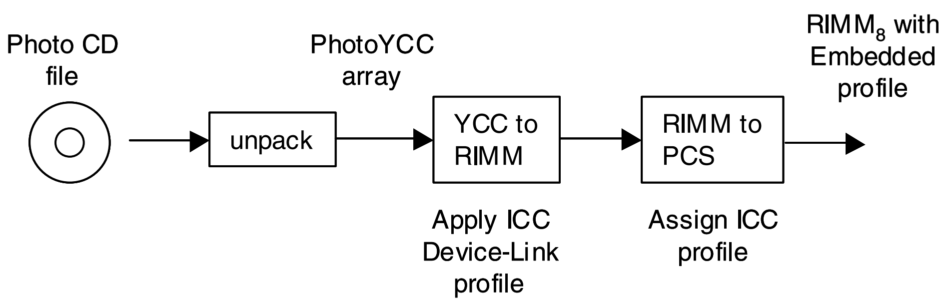

Figure 1: Transformation from Photo CD image file to RIMM

A device-link profile, which defines the relationship between the PhotoYCC and RIMM color encoding specifications, executes the desired data metric conversion, retaining the salient PhotoYCC original-subject nature of the image data. The use of a device-link profile is necessary to retain PhotoYCC's extended luminance dynamic range and color gamut in the RIMM RGB encoding. This information would be irretrievably lost if the conversion were embodied in a composite profile produced by concatenation of an input PhotoYCC-to-PCS profile and an output PCS-to-RIMM profile. The problem results when the image data passes through the International Color Consortium (ICC) Profile Connection Space (PCS). The PCS comprises a color-encoding specification of colors associated with rendered images to be viewed in a particular reproduced-image viewing environment. While the PCS was intended to be a color space where input and output device profiles could be joined to form composite input-to-output color transforms, it does not deal well with the extended nature of the encodings of interest in this paper. Use of a device-link profile avoids passing through the PCS, yet can be applied in an ICC-based color-management environment. In our case, the PCS *is* recommended in the second profile of the conversion process, due to the different purpose of that profile.

An assigned input profile, embedded in the image file itself, accomplishes the rendering of RIMM-encoded original-subject color values to ICC PCS values appropriate for display on imaging devices and media viewed in average-surround conditions. This rendering process entails necessary increases in the luminance contrast and chroma of the original subject colors, as well as imposing limits on the luminance dynamic range and color gamut dictated by the selected output medium or device capabilities. By relegating this lossy process to an assigned profile, the integrity of the stored image data is preserved and the rendering is executed on demand. The color-signal processing embodied in the device-link profile describing the relationship between PhotoYCC and RIMM is defined by the following transformation sequence.

Transformation of PhotoYCC Values to Original-Subject RIMM Tristimulus Values

In the first step of the transformation, luma and chroma values are computed from PhotoYCC Y, C_1, and C_2 digital color values. For 24-bit (8 bits per color channel) encoding, luma and chroma values are computed according to the following equations:

$$Luma = \frac{1.402}{255} Y$$
$$Chroma_1 = \frac{(C_1 - 156)}{114.40} \qquad (1)$$
$$Chroma_2 = \frac{(C_2 - 137)}{135.64}.$$

The resulting *Luma*, *Chroma₁*, and *Chroma₂* values are converted to nonlinear values, $R'G'B'_{709}$, using the following matrix transformation:

$$\begin{bmatrix} R'_{709} \\ G'_{709} \\ B'_{709} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ 1 & -0.194 & -0.509 \\ 1 & 1 & 0 \end{bmatrix} \begin{bmatrix} Luma \\ Chroma_1 \\ Chroma_2 \end{bmatrix}. \qquad (2)$$

The $R'G'B'_{709}$ nonlinear values are converted to linear exposure-factor values, RGB_{709}, using the following equations. For $R'G'B'_{709} \geq 0.081$,

$$R_{709} = \left(\frac{R'_{709} + 0.099}{1.099} \right)^{1/0.45}$$
$$G_{709} = \left(\frac{G'_{709} + 0.099}{1.099} \right)^{1/0.45} \qquad (3)$$
$$B_{709} = \left(\frac{B'_{709} + 0.099}{1.099} \right)^{1/0.45}.$$

For $R'G'B'_{709} \leq -0.081$,

$$R_{709} = -\left(\frac{R'_{709} - 0.099}{-1.099} \right)^{1/0.45}$$
$$G_{709} = -\left(\frac{G'_{709} - 0.099}{-1.099} \right)^{1/0.45} \qquad (4)$$
$$B_{709} = -\left(\frac{B'_{709} - 0.099}{-1.099} \right)^{1/0.45}.$$

For $-0.081 < R'G'B'_{709} < 0.081$,

$$R_{709} = \frac{R'_{709}}{4.5}$$
$$G_{709} = \frac{G'_{709}}{4.5} \qquad (5)$$
$$B_{709} = \frac{B'_{709}}{4.5}.$$

The RGB_{709} exposure-factor values are then converted to CIE $XYZ_{D_{65}}$ values using the following matrix transformation:

$$\begin{bmatrix} X_{D_{65}} \\ Y_{D_{65}} \\ Z_{D_{65}} \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix} \begin{bmatrix} R_{709} \\ G_{709} \\ B_{709} \end{bmatrix}. \qquad (6)$$

Note: In this and the following equations, the original-subject XYZ tristimulus values are normalized such that the Y *tristimulus value of a normally exposed perfect white diffuser in the principal subject area of the scene has a value of unity (1.0).*

The CIE $XYZ_{D_{65}}$ tristimulus values are then transformed to visually equivalent CIE $XYZ_{D_{50}}$ tristimulus values to account for the different adaptive whites of the PhotoYCC and RIMM color encoding specifications. A variety of methods can accomplish this transformation, including the following von Kries chromatic-adaptation matrix:

$$\begin{bmatrix} X_{D_{50}} \\ Y_{D_{50}} \\ Z_{D_{50}} \end{bmatrix} = \begin{bmatrix} 1.0161 & 0.0554 & -0.0522 \\ 0.0061 & 0.9956 & -0.0012 \\ 0.0000 & 0.0000 & 0.7576 \end{bmatrix} \begin{bmatrix} X_{D_{65}} \\ Y_{D_{65}} \\ Z_{D_{65}} \end{bmatrix}. \qquad (7)$$

The CIE $XYZ_{D_{50}}$ tristimulus values are then converted to *RGB* tristimulus values for the RIMM red, green, and blue primaries defined in Table 1 using the following conversion matrix:

$$\begin{bmatrix} R_{RIMM} \\ G_{RIMM} \\ B_{RIMM} \end{bmatrix} = \begin{bmatrix} 1.3458 & -0.2556 & -0.0511 \\ -0.5344 & 1.4987 & 0.0201 \\ 0.0155 & 0.0030 & 1.1974 \end{bmatrix} \begin{bmatrix} X_{D_{50}} \\ Y_{D_{50}} \\ Z_{D_{50}} \end{bmatrix}. \qquad (8)$$

Serial application of the matrix transformations of Eqs. 6, 7, and 8 can be equivalently accomplished by the single matrix transformation

$$\begin{bmatrix} R_{RIMM} \\ G_{RIMM} \\ B_{RIMM} \end{bmatrix} = \begin{bmatrix} 0.5229 & 0.3468 & 0.1303 \\ 0.0916 & 0.8599 & 0.0485 \\ 0.0236 & 0.1122 & 0.8642 \end{bmatrix} \begin{bmatrix} R_{709} \\ G_{709} \\ B_{709} \end{bmatrix}. \qquad (9)$$

RIMM tristimulus values then are transformed to 8 bits per channel nonlinear values, $R'G'B'_{RIMM}$, using a nonlinear transformation identical to that implemented in the Photo CD system:

For $0.0 \leq RGB_{RIMM} < 0.018$,

$$R'_{RIMM} = \frac{255}{1.402} 4.5 R_{RIMM}$$
$$G'_{RIMM} = \frac{255}{1.402} 4.5 G_{RIMM} \quad . \qquad (10)$$
$$B'_{RIMM} = \frac{255}{1.402} 4.5 B_{RIMM}$$

For $0.018 \leq RGB_{RIMM} \leq 2.0$,

$$R'_{RIMM} = \frac{255}{1.402} \left(1.099 R_{RIMM}{}^{0.45} - 0.099 \right)$$
$$G'_{RIMM} = \frac{255}{1.402} \left(1.099 G_{RIMM}{}^{0.45} - 0.099 \right). \qquad (11)$$
$$B'_{RIMM} = \frac{255}{1.402} \left(1.099 B_{RIMM}{}^{0.45} - 0.099 \right)$$

The resulting $R'G'B'_{RIMM}$ values are rounded to nearest integer values between 0 and 255 for digitization.

Relationship for Abstract Profile RIMM to PCS

The abstract profile expressing the relationship between RIMM RGB and the PCS must include compensations for the reductions in perceived luminance contrast and color saturation resulting from the PCS viewing conditions relative to those defined for RIMM RGB. This is accomplished using a reference rendering medium that provides a means for converting original-subject color values encoded with respect to a viewing environment consistent with that defined for RIMM RGB, to color values encoded with respect to a viewing environment normally associated with the viewing of reproduced images, consistent with that defined for the PCS.

The reference medium is defined conveniently in terms of red, green, and blue primaries, and an additive white point whose chromaticities are identical to those defined for RIMM RGB, and an associated grayscale-rendering characteristic. The rendering characteristic imparts the required compensations described above according to the relationship shown in the Fig. 2 below and enumerated in the accompanying Table 2 in the Appendix.

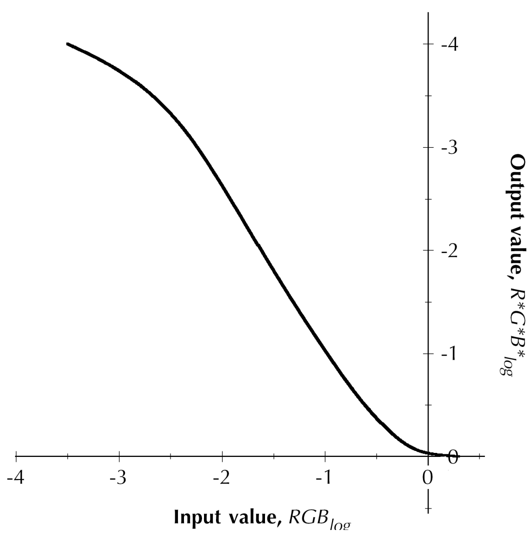

Figure 2: Equal RGB reference rendering medium grayscale characteristic.

It should be noted that the Modified $R^*G^*B^*_{log}$ values shown are consistent with the luminance dynamic range limits of the ICC PCS and entails compression of highlight detail in the rendered image, which may be undesirable when images are displayed on high-quality output devices and media. Applications with rendering capability beyond these limits can make use of the unmodified reference medium characteristic detailed in Ref. 6.

The 8-bit $R'G'B'_{RIMM}$ nonlinear values are first converted to linear exposure-factor values, RGB_{RIMM}, using the following equations.

For $R'G'B'_{RIMM} \geq 0.081$,

$$R_{RIMM} = \left(\frac{\frac{1.402}{255} R'_{RIMM} + 0.099}{1.099} \right)^{1/0.45}$$
$$G_{RIMM} = \left(\frac{\frac{1.402}{255} G'_{RIMM} + 0.099}{1.099} \right)^{1/0.45} \quad . \tag{12}$$
$$B_{RIMM} = \left(\frac{\frac{1.402}{255} B'_{RIMM} + 0.099}{1.099} \right)^{1/0.45}$$

For $R'G'B'_{RIMM} < 0.081$,

$$\begin{aligned} R_{RIMM} &= \frac{1.402}{255}\frac{R'_{RIMM}}{4.5} \\ G_{RIMM} &= \frac{1.402}{255}\frac{G'_{RIMM}}{4.5} \quad . \\ B_{RIMM} &= \frac{1.402}{255}\frac{B'_{RIMM}}{4.5} \end{aligned} \tag{13}$$

The logarithms of the RGB_{RIMM} exposure-factor values then are calculated:

$$\begin{aligned} R_{\log} &= \log_{10} R_{RIMM} \\ G_{\log} &= \log_{10} G_{RIMM} \quad . \\ B_{\log} &= \log_{10} B_{RIMM} \end{aligned} \tag{14}$$

The resulting RGB_{log} values are transformed to modified $R^*G^*B^*_{log}$ according to the relationship shown in Fig. 2 and listed in the Appendix:

$$\begin{aligned} R^*_{\log} &= f(R_{\log}) \\ G^*_{\log} &= f(G_{\log}) \ , \\ B^*_{\log} &= f(B_{\log}) \end{aligned} \tag{15}$$

and converted to linear values, $R^*G^*B^*$:

$$\begin{aligned} R^* &= 10^{R^*_{\log}} \\ G^* &= 10^{G^*_{\log}} \quad . \\ B^* &= 10^{B^*_{\log}} \end{aligned} \tag{16}$$

These values are transformed to CIE XYZ_{PCS} tristimulus values using the following matrix transformation:

$$\begin{bmatrix} X_{PCS} \\ Y_{PCS} \\ Z_{PCS} \end{bmatrix} = \begin{bmatrix} 79.67 & 13.59 & 3.17 \\ 28.42 & 71.57 & 0.01 \\ -0.96 & 0.00 & 83.47 \end{bmatrix} \begin{bmatrix} R^* \\ G^* \\ B^* \end{bmatrix} . \tag{17}$$

The resulting $CIE\ XYZ_{PCS}$ tristimulus values then are converted to CIELAB values, $L^*a^*b^*_{PCS}$, using the standard equations defined for the CIE 1976 CIELAB Color Space, which can be found in Appendix A of Ref. 6, and in numerous other references.

Finally, the resulting $L^*a^*b^*_{PCS}$ values are converted to digital code values, CV_1, CV_2, and CV_3, according to the 24-bit (8 bits per channel) CIELAB data metric defined for the ICC PCS. The digital code values are the nearest integers to the values determined from the following equations:

$$\begin{aligned} CV_1 &= 2.55L^* \\ CV_2 &= a^*_{PCS} + 128\ . \\ CV_3 &= b^*_{PCS} + 128 \end{aligned} \quad (18)$$

Note: If the unmodified reference media-rendering characteristic mentioned earlier is used, the scale factor in the equation for CV_1 *above should be changed from 2.55 to 2.10.*

Conclusions

For conversion of Photo CD master files, when the retention of color fidelity is a priority, consideration should be given to the several attributes of the currently stored color-image information. In many cases the legacy color encoding provides a link to the original-subject colorimetry. One path that retains the extended luminance range and color gamut characteristics of the PhotoYCC color encoding is migration to RIMM RGB color space. This conversion can be implemented using a combination of ICC device-link and embedded profiles.

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Author Biographies

Thomas Madden is a Principal Research Scientist at Eastman Kodak Company where he designs digital and hybrid color-imaging systems. A frequent speaker and instructor on color imaging, he is the co-author of Digital Color Management: Encoding Solutions. He is the inventor of the PhotoYCC color encoding specification, and holds numerous patents in the field.

Peter Burns is also a Principal Research Scientist with Kodak's Research Labs. His technical interests include image processing, system evaluation, and the statistical analysis of error in digital and hybrid systems.

Appendix

Table 2: Equal RGB reference rendering medium grayscale characteristic as shown in Fig. 2

RGB_{log} input value	Modified $R^*G^*B^*_{log}$ output value
<=–3.50	–4.00
–3.45	–3.98
–3.30	–3.91
–3.15	–3.83
–3.00	–3.74
–2.85	–3.64
–2.70	–3.52
–2.55	–3.38
–2.40	–3.21
–2.25	–3.01
–2.10	–2.79
–1.95	–2.55
–1.80	–2.30
–1.65	–2.05
–1.50	–1.80
–1.35	–1.56
–1.20	–1.33
–1.05	–1.10
–0.90	–0.88
–0.75	–0.68
–0.60	–0.49
–0.45	–0.32
–0.30	–0.18
–0.15	–0.08
0.00	–0.03
0.15	0.01
0.30	0.00