Issues Encountered in Creating a Version 4 ICC sRGB Profile

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Abstract

This paper addresses the issues and challenges encountered in creating a version 4 (v4) ICC profile. After a brief discussion of the major conceptual advancements of the v4 ICC framework over the v2 ICC framework, we describe as a case study the implementation of a v4 sRGB perceptual and colorimetric color-space profile. Although the ICC specification defines a reference medium and reference viewing conditions for the v4 perceptual rendering intent, it does not specifically define a reference medium gamut. Nevertheless one is needed. Within the paper we propose a reference medium gamut, which serves as a fuzzy target for the perceptual color re-rendering. It has been presented to the ICC for further consideration. The discussion of the goals and constraints used for the creation of the perceptual rendering intent should be helpful for the evaluation of the generated v4 sRGB ICC profile and for the creation of future v4 profiles. Visualizations of the perceptual mapping in comparison to the colorimetric mapping and discussions of potential improvements will conclude the paper.

Introduction

The International Color Consortium (ICC) was formed in 1993 by a few companies, and has since expanded to roughly 60 companies. It has developed a profile-based framework for color management, which has been widely implemented in different industries. ICC profiles provide color imaging systems with the information necessary to convert color data for reproduction on different devices. ICC profiles are categorized into 6 different classes (Input, Display, Output, ColorSpace, Abstract, DeviceLink and NamedColor), where each class specifies the applicability of the transformations to be performed by either the default OS or a third party Color Management Module (CMM). The transformations are specified using several different basic structural components, which distinguish themselves in terms of suitability, performance, precision, implementation complexity and memory requirements. The profile format has been revised from the version 2 (v2) format to the version 4 (v4) format, which is described in detail in the following ICC document: *ICC.1:2001-12 File Format for Color Profiles*. The following section will discuss the major conceptual differences between v4 and v2 profiles that have an effect on the implementation and use of v4 profiles in general and the v4 sRGB profile in particular.

V2 and V4 ICC Profiles Compared

One of the overall goals in going from v2 to v4 was to improve interoperability for properly constructed profiles. ICC workflows are supposed to work seamlessly with profiles generated by software from different companies, and the fact that this is not always the case has lead to a lot of frustration. One improvement in v4 is a more rigorous definition of the colorimetric and perceptual rendering intents. Version 4 ICC-absolute (the CIE XYZ values are relative to a perfect diffuser) and media-relative colorimetric (the CIE XYZ values are relative to a media white point) intents are required to be measurement based. Applying a colorimetric rendering intent of an input profile to image data results in a representation of the colorimetry of an original in the profile connection space (PCS). Likewise, colorimetric intent output profiles represent the expected colorimetry of the reproduction in the PCS. The image state (input-referred, output-referred) does not change. A media-relative colorimetric transformation maps the white point of the media to the white point of the PCS, keeps the relationships of in-gamut colors unchanged and clips colors out of the PCS gamut (if any) to the PCS gamut boundary. Colorimetric reproduction can be achieved by simply combining the profiles, where colors present in the original medium that are within the gamut of the reproduction medium are unchanged, while colors outside of the reproduction medium gamut are clipped. This reproduction goal is useful for proofing applications.

Alternately, a "smart" CMM may re-render the colorimetry of the original (as represented in the PCS), to colorimetry better suited for the reproduction medium and viewing conditions. When using the colorimetric rendering intents, the color re-rendering applied to produce the reproduction is either a null operation (except for clipping), or is deferred until the actual output medium is known and then performed by the smart CMM.

Applying a perceptual rendering intent to image data to go to the PCS performs a color re-rendering. By defining a perceptual intent reference medium and reference viewing conditions, the v4 specification provides a more precise PCS rendering target, which can be thought of as an intermediate image. The perceptual intent reference medium has a white point reflectance factor of 0.89, a black point reflectance factor of 0.0030911, and a viewing illumination level of 500lux with an average surround (ISO 3664 condition P2). The only aspect of the reference medium that has not yet been agreed upon is the reference medium gamut. A gamut is needed as a target for the color re-rendering included in perceptual rendering intents, and is currently at the discretion of the profile creation software.

The advantage of the intermediate image approach to color management over the deferred color rendering approach is that the color re-rendering is incorporated in the profiles, which allows it to occur without the CMM having to do it. This situation improves consistency over deferred (smart CMM) color re-rendering since different smart CMMs may employ different algorithms that produce different results. Combining specific input and output profile perceptual intents should always produce the same result. Furthermore, the quality of the intermediate image approach can exceed that of the deferred color rendering approach if the color re-rendering incorporated in the perceptual intents is superior to that performed by a particular CMM. This could often be the case because state-of-the-art color re-rendering algorithms are closely guarded trade secrets. The transforms resulting from applying these algorithms can be placed in profiles without giving away too much about how the algorithms work, but including an algorithm in a CMM to perform general color re-rendering opens up its operation to anyone who wants to take the time to probe the CMM. Also, in some cases, the color re-rendering transforms produced by the proprietary algorithms are manually optimized (tweaked). Such optimizations can be included in profiles.

One other important point is that unlike v2, v4 input-side profiles can contain multiple rendering intents. There are a few other differences between v4 and v2 profiles, but within this paper we will focus on issues of particular relevance to the implementation of the sRGB v4 profile.

HP Perceptual Intent Reference Medium Gamut Target

The v2 ICC specification does not define a perceptual intent reference medium beyond the statement that it represents an "ideal reflection print". Indeed, it is not practical to define one for v2 input profiles because multiple rendering intents are not allowed. Therefore, it is often unclear to which degree the input profile is performing color rendering. Historically, some v2 input profiles have represented the colorimetry of the original in the PCS, similar to the colorimetric intent of v4 input profiles. Other v2 input profiles apply only black point scaling to the original colorimetry (like the v2 sRGB profile). Finally, v2 input profiles can also be found that perform full color re-rendering to represent the "ideal" image colorimetry in the PCS.

Whatever colorimetry is represented in the PCS, it is the job of the v2 output profile perceptual intent to re-render the PCS colorimetry appropriately for the specific output medium. This is an impossible task, because the output profile has no advance knowledge of what it is starting from. Thus, everyone creating perceptual rendering intents for v2 profiles makes their own assumptions about what to render from in the PCS. The assumptions made by one person might not be the same as those of another person, which results in interoperability issues. Even if the same assumption was made by everyone as a starting point for output profile perceptual intents, it would not always be appropriate for the input profile used, which would then result in quality degradation as the image colorimetry in the PCS deviates from the assumption.

This issue became apparent as ICC color management was implemented. As a response, some profile creators started creating input and output profile pairs that are constructed based on a common assumption about the intermediate image colorimetry. This enabled working ICC v2 systems that include color re-rendering. However, the result of this situation is that, except for colorimetric reproduction with black point scaling, ICC v2 is largely only a standard format for color transforms. There is no guarantee that different v2 profiles will work well with each other.

With ICC v4, the inclusion of explicitly defined, multiple rendering intents in input-side profiles, and the defined perceptual intent reference medium and viewing conditions clearly improve the possibilities for increased interoperability. Only the reference medium gamut is missing.

In the process of creating an sRGB v4 profile with a perceptual rendering intent, we needed a clearly defined rendering target gamut. Thus, without a reference medium gamut defined by the ICC, we had to define one ourselves. Our constraints were that it had to be print-referred with a shape similar to the general shape of printer gamuts, that it should be a superset of a representative set of actual printer gamuts, and that the relationship of the new gamut and silver halide gamuts be taken into consideration. The resulting target gamut is shown in figures 1a and 1b (transparent yellow) in comparison with the gamut of an actual HP inkjet printer on glossy photo media (color wire frame), which we included as an example. Figures 1a and 1b show the same gamuts from different points of view and illustrate that the reference medium gamut encompasses the gamut of the example ink jet printer while retaining a general print-like shape. The same holds true for other printer gamuts.

The proposed HP reference medium gamut has been presented to the ICC. However, any commonly agreed upon target gamut improves interoperability. Our proposal attempts to achieve interoperability while maintaining high-end quality. For our current implementation of an sRGB v4 profile, we used the reference medium gamut as a fuzzy target for the color re-rendering process.

Figures 2a and 2b compare the reference medium gamut (transparent yellow) with the re-rendered sRGB gamut (sRGB gamut to which the perceptual rendering intent of the v4 sRGB profile has been applied). The comparisons are made in the CIE L*a*b* space. The visualization shows how similar the target and the actual re-rendering gamuts are.

Figures 3a and 3b compare the sRGB gamut to the re-rendered sRGB gamut to show the nature of the color re-rendering. By accomplishing the more aggressive re-rendering from sRGB to the reference medium on the input side, the second re-rendering from PCS to the actual print medium becomes mild. This makes it easier to create output profile perceptual intents, and improves the consistency of results with different printers since they all tap the same display-to-print input-side re-rendering.

Creation of the Perceptual Rendering Intent of an sRGB v4 Profile

This section describes the core objective of this work. Creating a good display to print perceptual rendering has been the most challenging and at the same time most interesting part. The result of this work, an sRGB v4 profile, is now available to ICC members via the ICC web page (http://www.color.org). We have tested it thoroughly for correct form and functionality and are continuing to improve the "look" of the color re-rendering it contains.

By sharing the profile, we hope to get feedback on its performance and quality, and for it to serve as an example for other v4 profiles. Applying the profile to random sRGB images and printing them on a large gamut printer using a simple colorimetric profile on the output side will reveal its performance. Applying it to a set of regularly spaced RGB patches reveals the resulting gamut as well as the re-rendering transformation. Thus, we encourage readers to test the profile and offer feedback.

The profile contains a 33-cubed 3D LUT going from a regular grid in sRGB to CIE LAB, and a 33-cubed 3D LUT going from a regular grid in LAB to sRGB. Not surprisingly, it turned out that the sRGB to LAB map was easier to create than the inverse LAB to sRGB map. One of the decisions in creating any profile is determining the appropriate number of sampling points to be used in the 3D LUT. The number of sampling points should be large enough to accurately model the re-rendering, while at the same time, should be small enough to have a reasonably-sized profile.

Another question is how to generate a regular grid in LAB that inverts the forward transform from the irregular points that one gets from applying a perceptual rendering intent in the forward direction to a set of regular spaced sRGB values. An additional challenge is that blocking artifacts can easily occur in the backwards direction. It turned out that it is very helpful to use an sRGB gradient image containing the surfaces of an sRGB cube, convert it to LAB using the sRGB v4 profile, then to go back to sRGB using the same profile. Blocking artifacts can very easily be identified in those kinds of test images.

According to the ICC profile specification, inverses of the perceptual intent transformations have to be provided. The invertability can easily be tested by applying the profile in the forward and backward direction and by comparing the original image with the transformed image. They should be as close as possible. Another helpful tool is to have a visualization tool (gamut viewer), which enables a comparison of the gamuts of different profiles. And last but not least applying the profile to a representative set of images always reveals the qualities and shortcomings of the transformations. Given a sufficient variety of test images, it is impossible to hide them.

Implementation of the Media Relative Colorimetric Rendering Intent of an sRGB v4 Profile

The implementation of the v4 sRGB media-relative colorimetric intent is overall very similar to a traditional v2 sRGB colorimetric intent. The main difference is that the v4 is required to be measurement based so black point scaling is not included in the profile. This is different from v2 profiles, where black point scaling was allowed to be included (which was the case with the v2 sRGB profile). Simple scaling is not always an adequate method for black point compensation. Thus, for v4 profile colorimetric intents, black point compensation should be handled by the CMM, where more sophisticated proprietary methods can be used.

Because we used LAB as the PCS for our perceptual rendering intent to improve invertability, we were forced to use it as the PCS for our colorimetric rendering intent as well (the ICC Specification only allows for one color space to be specified for the entire profile). As it turned out, the colorimetric transformations were a little more complicated when going to and from LAB than XYZ, which was the PCS that was used in the sRGB v2 profile. We ended up using lutAtoBType and lutBtoAType tags with parametric curves, which are new structures defined in the v4 specification.

Using the Perceptual versus the Colorimetric Rendering Intent of the sRGB v4 Profile

The generated v4 sRGB profile contains a perceptual transformation as well as a colorimetric transformation. This begs the question: what does it mean to apply a perceptual rendering intent to an sRGB image as opposed to applying a colorimetric intent?

In the first case, we are re-rendering an image from the sRGB reference display to the ICC perceptual intent reference medium. Thus, once the image data has been transformed to the PCS, it is in a print-referred state and can be transformed into device dependent values in an easy and straightforward way. Comparing the reference medium gamut of the PCS with actual printer gamuts shows the simple changes that are necessary in order to go from the PCS to different printers. Furthermore, the differences in going to printer A versus printer B should be rather small, and as a result, the appearance of the final images printed on different devices should be very similar.

In the second case, by applying a colorimetric intent to an sRGB image, we are not performing any re-rendering. Instead, we are just representing the colorimetry of the image within the PCS. This is useful for applications where we just want to achieve a colorimetric reproduction, like in proofing, or for display of an image on an output device with sRGB-like characteristics. Another scenario would be to provide a colorimetric input profile and a colorimetric output profile to a smart CMM and let it perform the optimal rendering going “directly” from the input side to the output side. This is a scenario that might be available in the future, and there have been discussions surrounding this topic, but currently , with the exception of black point compensation, none of the available CMMs implement such features.

Testing the Performance of the sRGB v4 Profile

Having generated the sRGB v4 profile we were eager to test it and evaluate its performance. Currently, there are only a few applications that support v4 profiles, one of which is Adobe Photoshop 7.0, which we chose to use for our testing. To test the profile, we assigned the profile to arbitrary sRGB images, applied the profile by converting the image to LAB, and then applied the profile in the other direction by converting the image back to sRGB. We then compared the original image with the transformed image. Another test was to combine the sRGB v4 profile with a colorimetric output profile for a large gamut printer and subjectively evaluate the results using both the colorimetric and perceptual intents on the input side, essentially proofing the colorimetry in the PCS in each case. We used sRGB images with pictorial content as well as test patches, which revealed a problem with the rendering of the black point.

According to the ICC specification and to the PIMA 7667 specification, (which specifies the sRGB black point and provides recommendations for creating ICC profiles), the LAB values associated with an sRGB triple of (0,0,0) should depend on the rendering intent and whether the CMM black point compensation is turned on or off. Table 1 contains the expected values. What we were actually getting using Adobe’s CMM and Apple’s CMM is displayed in table 2. Obviously, we did not get the expected L* values when we applied the perceptual rendering intent to a black patch. In order to verify our profiles we implemented a CMM in Matlab and got the correct result. We discovered that putting the tables for the perceptual intent in the place where the colorimetric tables should be and applying this fake colorimetric profile yielded the correct results. Discussions with a scientist from Adobe revealed that Photoshop’s LAB is equal to ICC v2 PCS LAB. In ICC v2, the perceptual intent PCS colorimetry is both media white and black point scaled, and there is no defined reference medium black point. Adobe chose a black point of L* = 0, which is consistent with the ICC v2 perceptual intent black point scaling. When we apply a v4 profile in Photoshop 7.0 to an sRGB image, Photoshop combines our v4 profile with their v2 LAB profile. The CMM maps the v4 perceptual intent black point (L*=3) to the v2 perceptual intent black point (L*=0). Effectively, Adobe’s CMM always applies black point compensation when the perceptual intent is used and one or both profiles are v2.

Table 1. According to the ICC specification for v4 sRGB profiles, the black point sRGB(0,0,0) should be transformed to the values in this table.

	Black Point Compensation OFF	Black Point Compensation ON
Perceptual Intent	*L* = 3*	*L* = 0*
Colorimetric Intent	*L* = 11*	*L* = 0*

Table 2. Using Photoshop 7.0 on Mac OS9.1, sRGB(0,0,0) is mapped to the values in this table.

	Black Point Compensation OFF	Black Point Compensation ON
Apple CMM		
Perceptual Intent	*L* = 0*	*L* = 0*
Colorimetric Intent	*L* = 11*	*L* = 0*
Adobe CMM		
Perceptual Intent	*L* = 0*	*L* = 0*
Colorimetric Intent	*L* = 11*	*L* = 0*

Within ICC v4, the perceptual intent PCS colorimetry is not black point scaled as in v2, but there is a defined reference medium black point and as a consequence there is no need for black point compensation when combining v4 perceptual intents.

To get the full v4 functionality and behavior it is necessary that all the profiles used are v4 profiles. Photoshop 7.0 does not support v4 LAB profiles. Nevertheless, one way to get v4 PCS colorimetry into Photoshop LAB is to use an input profile where the perceptual intent 3D CLUT is placed into the colorimetric intent. This causes Photoshop to apply the v2 LAB colorimetric intent on the output side, which maintains the v4 perceptual intent colorimetry.

Another requirement of a v4 profile is invertability: the lutBtoAType transformation should be the inverse of the lutAtoBTupe transformation. In order to test this feature and especially the smoothness of the lutBtoA transformation, we used an sRGB gradient image containing the surfaces of an sRGB cube and applied the sRGB v4 profile in the forwards (sRGB to Lab), and afterwards in the backwards (Lab to sRGB) directions. That test revealed visible blocking artifacts in the final sRGB image, if the original sRGB image was in an 8-bit mode. The artifacts were there regardless of whether Photoshop's CMM or our Matlab CMM was used. Changing the original image from an 8-bit mode into a 16-bit mode removed the artifacts.

The above-mentioned gradient image also showed that our transformations are smooth both in the forward and in the backwards direction. In general, this cannot be taken for granted. Depending on the size of the LUT, the method used to generate the inverse map, the type of interpolation used, and on the fuzzy interpretation of the reference medium gamut, artifacts can occur very easily, especially in the backwards direction (in our case from LAB to sRGB). It takes some effort and it is a combination of science and art to improve the quality and get it closer to a perfect solution.

Another helpful step in the creation of an ICC profile is to visualize the profile in a gamut viewer using 2D and/or 3D diagrams. An extension of that is to take a discrete number of regular samples in sRGB, generate an image of patches and send it through the colorimetric and perceptual profile and then compare the resulting LAB points with each other. Figure 4 does exactly that. The figure is a parallel projection of the resulting LAB points onto a plane. The lines connect the colorimetric values with the corresponding perceptual values. Diagrams like that can be used to visualize the transformation and can also be used to improve the color re-rendering.

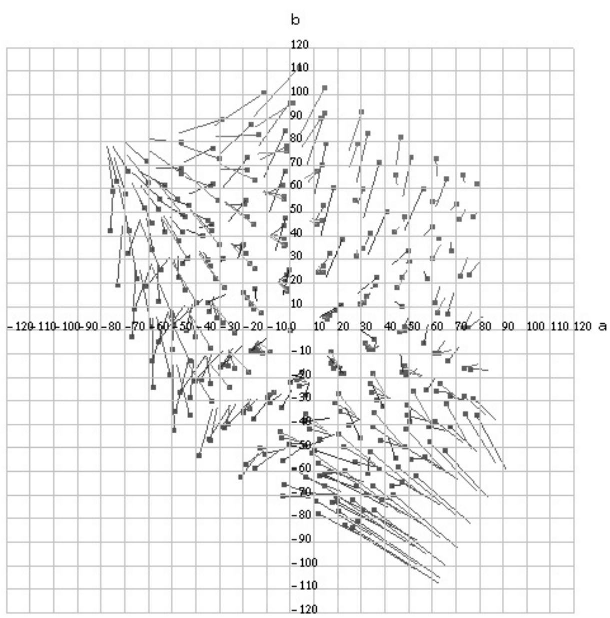

Figure 4. Comparison of the result of the colorimetric rendering intent of the new v4 sRGB profile (starting points of the lines) with the result of the perceptual rendering intent of the profile (black squares) applied to regularly spaced RGB samples.

Perhaps the best way of testing a version 4 profile is by combining it with other profiles and applying it to a lot of different images. Furthermore, it is always easier to compare two images and judge them relative to each other than to judge them just by themselves. Figures 5 through 10 compare images re-rendered to the PCS with a v2 ICC sRGB profile to the same images re-rendered to the PCS with the perceptual intent of the v4 ICC sRGB profile. In both cases, the images are finally transformed via a media relative colorimetric intent to the gamut of an HP Indigo 3000 press and printed on that machine. The advantages of the second set are visible in the perceptually more accurate reproduction of the blue of the sky, the smoother transitions from black to dark blue in the sky, and the more pleasing and natural reproduction of skin tones, foliage and fruits.

Potential Improvements

We have identified a couple of potential improvements. First we would like the ICC to agree on a particular reference medium gamut in order to insure true interoperability with input-side color re-rendering. Second, we will further test our profile on a larger set of images, and combine it with different printer profiles. Naturally we also want to generate v4 perceptual rendering intent printer profiles in order to test the full potential of v4 profiles. The preferred rendering of memory colors is another area of potential improvement.

Conclusion

We have described the creation of a v4 sRGB ICC profile and thereby elaborated on: the differences between v4 and commonly used v2 profiles, the constraints and thoughts leading to the definition of a reference medium gamut, the details about the implementation of the perceptual and colorimetric rendering intents, the situations when to use the colorimetric intent of the new profile and when to use the perceptual intent, the methods used for visualizing, analyzing and testing the new profile, the issues encountered when using it in Photoshop 7.0, and the potential improvements. Overall, we are encouraged by the quality of the images produced by the v4 sRGB ICC profile, and we are optimistic that the improvements in interoperability and consistency that are enabled by v4 ICC profiles will lead to more satisfying color management solutions.

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Biography

Kok-Wei Koh earned his B.S. with distinction in Computer Science (magna cum laude) from the University of Washington, Seattle, Washington, in 1994. He joined Hewlett-Packard's Vancouver Printer Division in 1997 and developed software drivers and color tables for the company's inkjet printers. He has been working in the color imaging and printing technologies department of Hewlett-Packard Laboratories, Palo Alto, California since 2000, and earned his M.S. in Computer Science from Stanford University in 2002.