Three Component Color Representations for Graphic Arts

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This paper and the contribution from William Kress, which follows, review scientific and engineering considerations pertinent to the specification of standards for exchange of color images. The focus of the discussion is device independent (and, therefore, three dimensional) color notations. The relevance is to "desktop" application software which finds increasing use in Graphic Arts production cycles. The goal is to establish defaults which dovetail industry conventions with de facto *standards promoted by the application developers. Reasons for proposing several defaults will be discussed as will proposals for the default definitions and their technical and scientific underpinnings.*

Introduction

Three of the most influential players in "Desktop Publishing" have announced or introduced products and image-handling conventions based on device independent color. TIFF 6.0 (TM Aldus), PostScript Level II (TM Adobe Systems) and ColorSync (TM Apple Computer) represent *de facto* standards for processing color images. Each convention provides a framework for colorimetric interpretation of a digital pixel's color coordinates.

In this paper we consider the problem of exchanging color image data from a high-level perspective. We then explore standard ways of dealing with the problem which are emerging from companies involved in DTP. It will be shown that these *de facto* standards are as yet fairly primitive and general, leaving developers ample flexibility to specify the details of color notations for representing images. Then we will discuss the efforts of standards writing organizations (especially the ANSI IT8 subcommittees) to codify the *de facto* standards in such a way as to advance the interests of the Graphic Arts industry. With this background we will discuss three color notations which are under consideration by standards committees. One is based directly upon the TriStimulus Variables of the 1931 CIE Standard Observer, another on 1976 CIELAB derived from those TSVs and a third, "calibrated RGB" representation exactly derivable from TSVs. We will present detailed proposals and rationales for the first two spaces. Mr. Kress will provide detailed discussion of the RGB image representation.

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Figure 1 suggests an evolving picture of facilities for graphic preparation for volume reproduction of color images. Increasingly, the means of production consist of networked computers and devices bound together by applications which are purchased from different companies and which are specialized for different roles in the preparation of color pages. Proper functioning of this arrangement requires that pages and page constituents be exchangeable through commonly understood conventions for document, image and color representation (or, less desirably, that dedicated interfaces be developed for all possible combinations of devices and applications.)

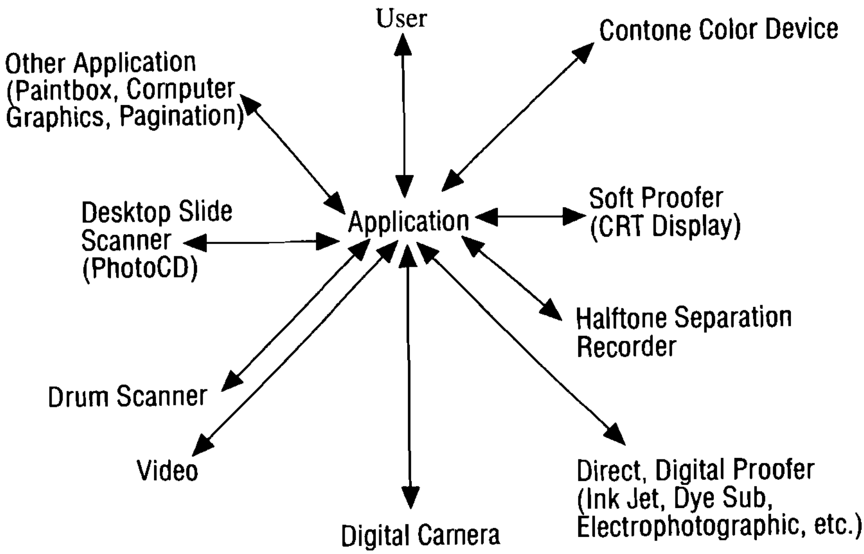


Figure 1: Schematic of facilities for distributed graphic preparation.

At the hub of Figure 1 is an application through which the user interacts with devices which may include other applications for gathering, integrating or rendering documentary constituents. On the left side are shown devices which supply input to document preparation and on the right are output devices. Hidden functions in the output interfaces may include screening and rasterizing; these functions are served by utilities or devices. "Color management" is a function hidden in virtually all the interfaces suggested by the diagram; color utilities attend to converting device independent specifications for images into other representations, either device independent or dependent.

Figure 2 focusses on the roles of color utilities. They apply (and, possibly, prepare) transformations between device signals and a portable image representation. This usually entails some accomodation to the gamuts of devices, possibly including the image representation itself. Translation of white points is usually required at one or more points in prepress work flow to accomodate changes in effective illumination and viewing conditions.

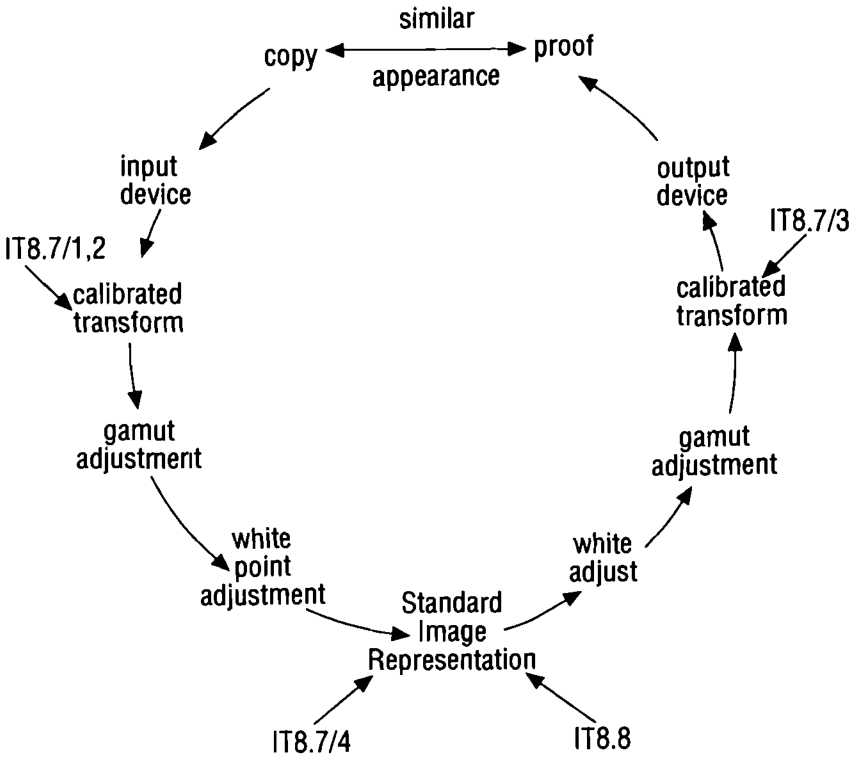


Figure 2: Steps of color image transformation in device independent prepress, showing points to which ANSI IT8 standards apply.

Subcommittee 4 (SC4) of the ANSI IT8 Committee has written standards (1992) specifying targets which aid in the process of creating the calibrated transforms shown in Figure 2. SC4 is now drafting a standard (1993) which addresses standardized color notations which are to be part of the image representation. Gamut representation and mapping techniques are fairly proprietary parts of color management systems and are not currently addressed by any IT8 standards activity. Subcommittee 2 of ANSI IT8 has recently ballotted the TIFF/IT standard (1993) which deals with other aspects of the standard image representation and links to the *de facto* standard TIFF image representation sponsored by Aldus Corporation.

The Influence of Aldus' TIFF

Revision 6.0 of the Tagged Image File Format, published by Aldus (1992) has several enhancements of interest to the Graphic Arts community. These include CMYK image definition, as well as CIELAB and YCbCr image definition and generalized RGB colorimetry. TIFF provides increasingly rich facilities for representing raster images which originate from scanners and computer graphical sources, the input side of Figure 1. Figure 3 suggests the layout of tagged image files. A simple file header points to the location in the file of the initial *Image File Directory*. The first element in the directory contains the number of entries, or *fields*. Each entry consists of a numeric tag, followed by a data type (e.g., byte, rational number, etc.), a count and a value or a pointer to where in the file the value can be found.

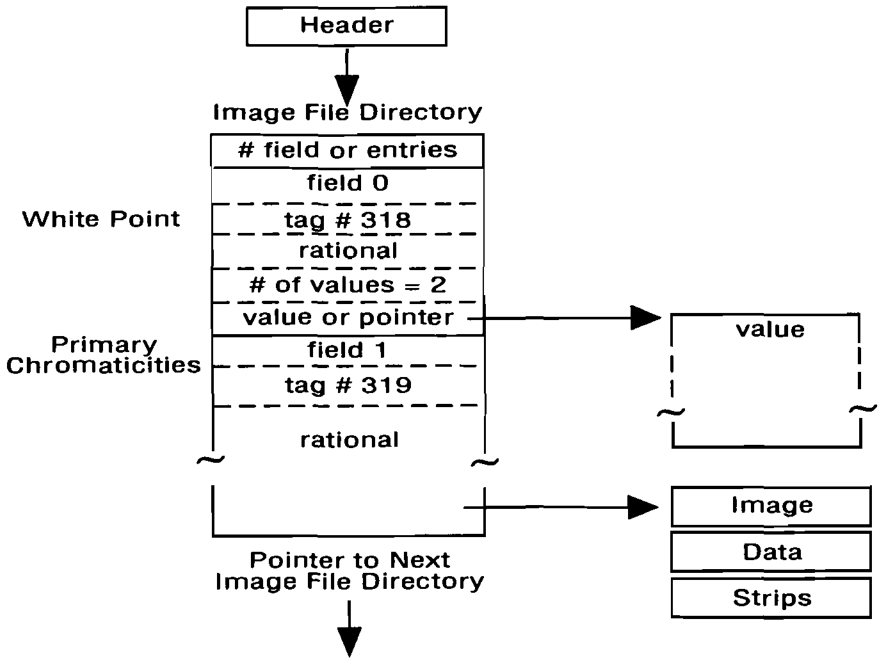


Figure 3: Outlines the organization of a "calibrated RGB" image file represented in Aldus Tagged Image File Format, rev. 6.0.

In our example the image data are stored as RGB with a colorimetric interpretation, as newly supported in rev. 6.0. The CIE TSVs, XYZ, themselves can be treated as a special case of this calibrated RGB. The tags which define images of this sort are: 1) *WhitePoint,* tag # 318, which uses two rational numbers to represent the x,y chromaticity of white, 2) *PrimaryChromaticities,* the x,y chromaticities of the RGB primaries (count = 6 rationals), 3) *TransferFunction,* which can be three distinct nonlinear encoding/decoding functions applicable to the three channels of data, 4) *TransferRange* and 5) *ReferenceBlackWhite.* The first two fields provide information necessary to convert between linearized pixel RGBs and XYZ. The 6.0 extension allows pixel components to exceed 8 bits. The third field describes companding or "gammatization" functions of the sort used to precondition RGB signals for a simple frame buffer and to permit more efficient quantization of data. Fields four and five have to do with slope and intercept aspects of the representation, i.e., how physical or psychophysical quantities are mapped onto a positive range of values for quantization.

Fields describing how to interpret compressed data might be included in the IFD and eventually fields specifying image dimensions and interleaving, and pointing to the image data itself would be included. Fields 1 and 2 of the colorimetric specification fields described above have no defaults, while field three is defaulted to a single table embodying what the NTSC considers a standard monitor gamma (2.2). In contrast to the situation for calibrated RGB, new, TIFF CIELAB is fully specified. We will compare TIFF 6.0 with SC4's recommendations for CIELAB later in the discussion of quantization issues.

Summary: Our review of TIFF colorimetry can be summarized with a few points. 1) Consideration of the tags and fields suggests why TIFF is oriented to input. It is not clear how rendering prescriptions can be associated with the file. 2) The absence of certain defaults provides an opportunity for the Graphic Arts industry to make recommendations in the light of its traditional standards.

New Color Graphic Provisions of Adobe's PostScript Level II

In the language definition of Level II of PostScript (TM, Adobe Systems, 1990),) an assortment of new graphics operators are introduced to enable conversions among device independent color spaces (see Chapter 4). Means of converting to device signals are described in Chapter 6 on rendering. The graphical operators are of three basic types:

a) Encoding/decoding operators serve the purpose of linearizing data which have been transformed nonlinearly for more efficient storage or the converse; the functions are applied to one channel at a time and can be different for each channel. They are often referred to as companding functions.

b) Range-setting functions serve the purposes of establishing slope, intercept and normalization on a channel-by-channel basis in a transformation pipeline.

c) 3 X 3 Matrix transformations are supported which enable linear mixing of the color channels.

The Reference Manual (1990) describes a pipeline in which each of the foregoing classes of operators is used more than once for a colorimetric conversion from one supported space to another. For example, the sequence of steps from Kodak's Photo YCC (1991) space to the CIE TriStimulus Variables, X, Y and Z involves unquantizing the Y, c1 and c2 values by a kind of range operation, followed by matrix transformation to a companded form of "calibrated RGB", followed by uncompanding to a linear form of the RGB by a decoding function. Decoded RGBs may then be converted to TSVs by a matrix operator and the TSVs renormalized by a range operator. This computation pipeline is depicted in Figure 4.

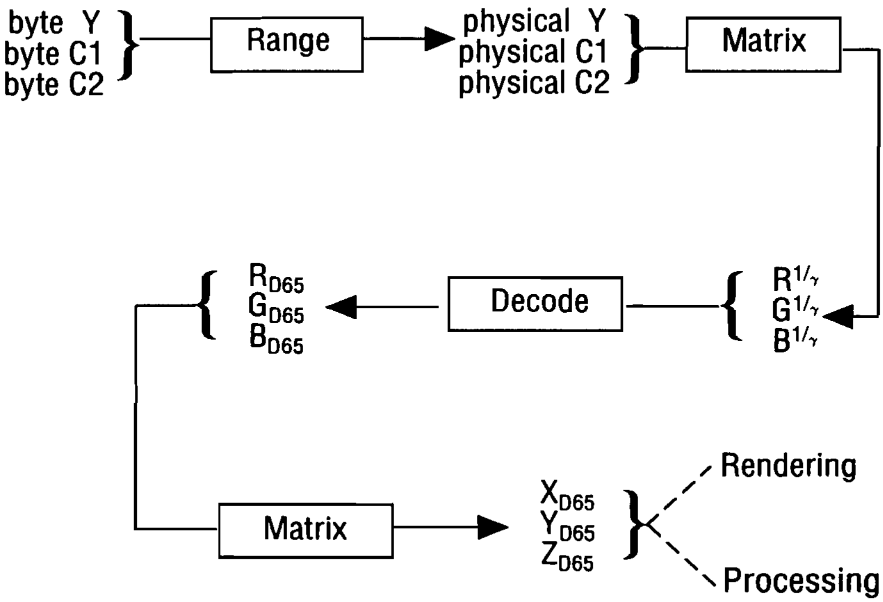


Figure 4: Transformation pipeline for converting from Kodak PhotoYCC to CIE TSVs showing, in boxes, relevant Adobe PostScript Level II operators.

An analogous pipeline can be fashioned to convert into and out of CIELAB (1978). It is doubtful whether one would want to convert large numbers of image values through such a pipeline and end up with TSVs which require many more than 24 bits for adequate precision, but such is what is made explicit in the language definition. Color notations which are supported by this mechanism are XYZ, "calibrated RGB", CIELAB and several luminance/chrominance representations such as PhotoYCC, NTSC

YIQ, etc. Operators are also provided for defining white point and black point. Therefore, all the ingredients for colorimetric conversions among linearly related spaces or their companded versions are provided.

Summary: TIFF is input-oriented; PostScript is output-oriented. While neither offers a framework which is as general or as efficient as possible both take decisive steps in the direction of supporting device independent color and neither purports to be a *system* solution for color management. Our review of the two *de facto* standards reveals their frameworks to be remarkably similar. This is for the good reason that they are addressing the same problem and attempting to allow developers flexibility in customizing solutions. We have not reviewed Apple ColorSync for reasons of space and history. Not enough has been public about it to have had a significant influence on SC4's deliberations thus far.

Why Three Color Notations?

Last year, we presented at TAGA (1992) a list of desirable attributes for color image representations and a discussion of how several popular spaces performed with respect to the list. We noted that properties favoring the exchange of image data were a subset of those facilitating image processing. From the list of attributes, key considerations for SC4 have been simplicity of computations on simple hardware, ability to support white point conversions and ability to accomodate the gamuts of Graphic Arts media. The committee stressed the former because the draft standard is meant to influence low-end, or DTP applications used in Graphic Arts environments. These applications are oriented toward the CRT and tend to run on platforms using inexpensive RGB frame buffers.

SC4 deliberated extensively on a single recommended default color notation for image exchange based on "calibrated RGB" and eventually concluded that there were too many compromises involved in doing so. Among them were inadequacies of gamut representation which will be addressed in detail in the companion paper. In considering which multiple spaces to standardize, the committee was influenced by the *de facto* standards described in previous sections. Those image handling conventions support, in a general way, digital representation in terms of CIE TriStimulus Variables, CIELAB and "calibrated RGB" along with various luminance/chrominance spaces derived from it. In our results section we will analyze technical issues of specifying defaults for notations based on XYZ and CIELAB.

Results

The presentation of results will emphasize data on white point adaptation and on encoding and quantization.

Handling of White Point Adjustments

The draft standard will not specify how gamut compensations or white point adjustments should be done. However, an important consideration in evaluating candidate color notations has been whether they lend themselves to handling the changes in lighting and viewing conditions which are typical in our industry. The implicit mapping of neutrals under one illumination to neutrals under another by CIELAB and CIELUV has often been cited as an advantage of those spaces in imaging applications.

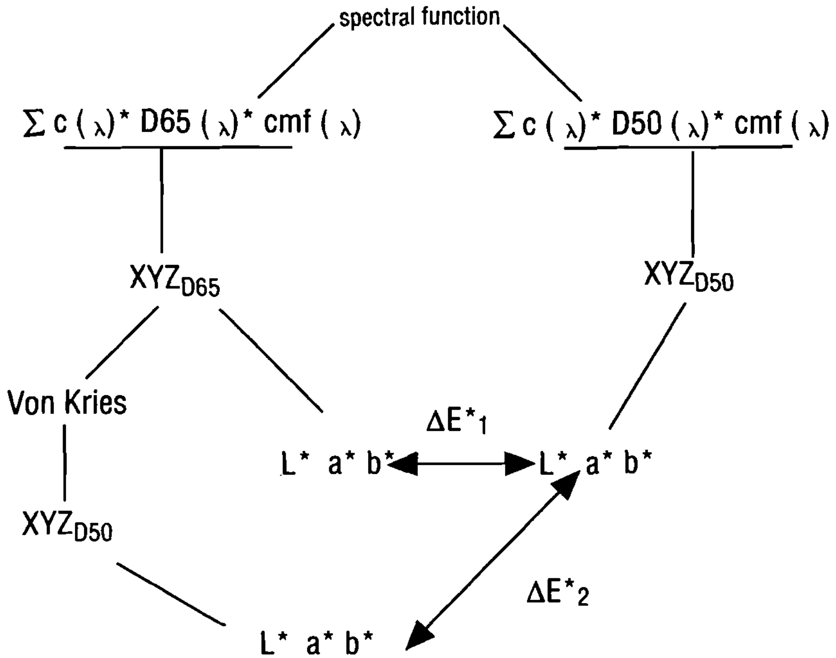


Figure 5: Design of experiment for evaluating effectiveness of two simple models of white point adaptation, that provided by CIELAB and a von Kries transformation.

For color spaces such as XYZ or calibrated RGB, a von Kries transformation is often recommended for modifying image values to anticipate modified viewing conditions properly. Therefore, we prepared a comparison of two approaches. One involves converting XYZs based on one illuminant to CIELAB or CIELUV, using the

XYZs or chromaticities of the illuminant (or the illuminant reflected off stock or shown through base plus fog) and then "adapting" by converting from Lab or Luv back to XYZ using the chromaticity of the new illuminant. The other approach would convert to a new XYZ using a von Kries transformation as described by Hunt (1991).

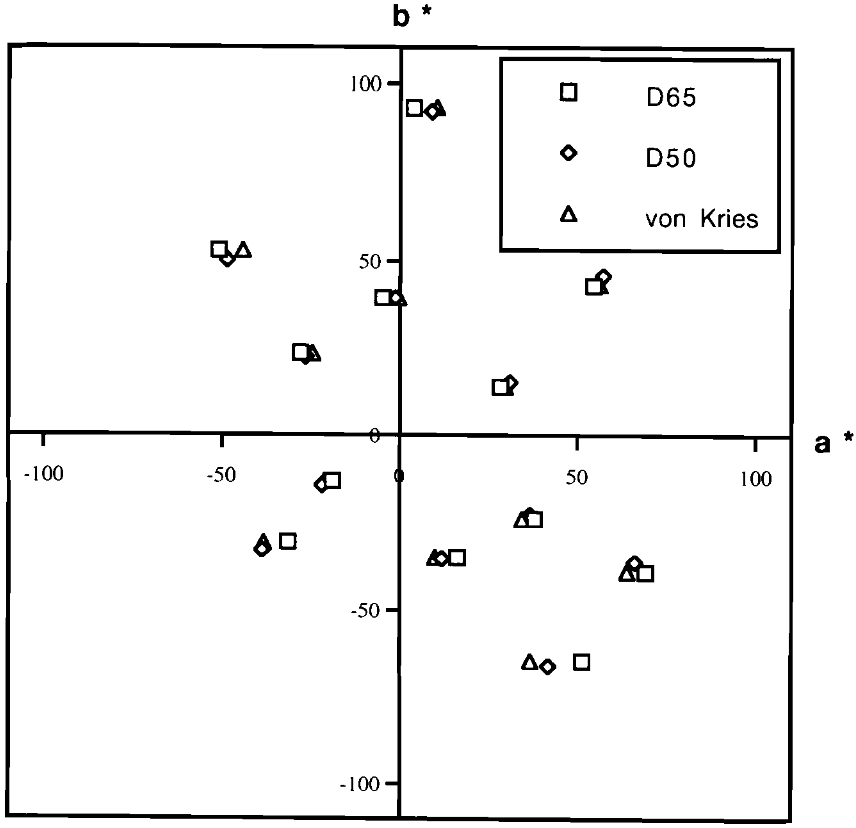
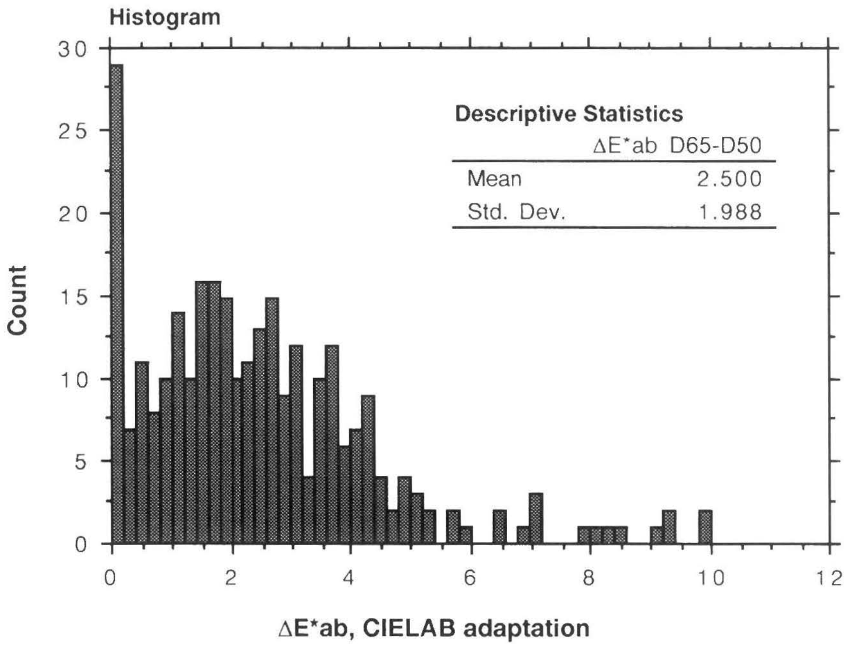


Figure 6: CIELAB diagram containing coordinates of reference colors (squares) derived from spectral data using D65 illumination and estimates of those colors based on CIELAB (diamonds) and von Kries (triangles) models of white point adaptation.

Figure 5 outlines the experimental approach. Data for the comparisons come from spectral measurements of the 288 patches in the IT8.7/1 film calibration target for scanner calibration. We convolved the relative transmissions of the patch measurements with D50 and D65 sources to obtain TSVs. We then converted to CIELAB using XnYnZn of D50 and D65, respectively. If CIELAB models chromatic adaptation well, the coordinates of an arbitrary color relative to neutral should be the same for the two illuminants.



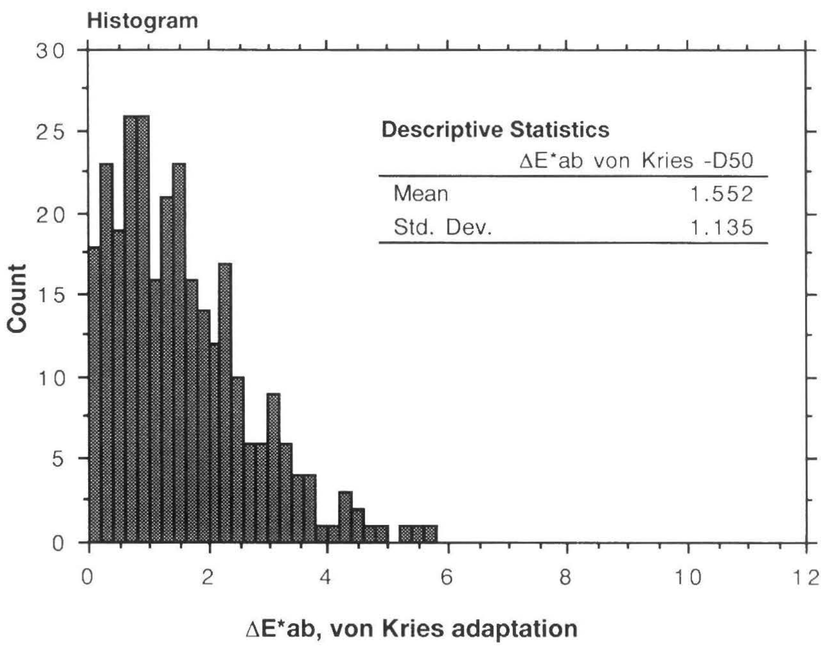


Figure 7: Summary of color error statistics for two simple models of white point adaptation.

CIELAB color differences provide a measure of the efficacy of adaptation. For comparison, we also converted D65 TSVs to D50 TSVs through a von Kries transformation before converting to CIELAB to see if the color error were reduced.

Results for a dozen colors of high and intermediate saturation are plotted in Figure 6. The colors were taken from the dye scales of the IT8 transparency, columns 13 through 15 and 17 through 19. Square symbols show the result of direct tristimulus integration with D65, diamonds of integration with D50. The triangles show the result of an intermediate von Kries adaptation from D65 to D50. In these data, the von Kries method looks worse, if anything. What is disturbing about either adaptation procedure is that hue angle is not preserved.

Data for all 288 patches are presented in histogram form in Figure 7. The von Kries procedure has better overall statistics. We have compared proofs of images modified for viewing differences in the two ways. Our preliminary conclusion is that a von Kries adjustment may result in a modest improvement, but more work is needed. In summary, von Kries adaptation provides a means of correcting TriStimulus Value-like color spaces for changes in viewing conditions, albeit at some computational cost.

Encoding and Quantization

A basic aspect of defining a default digital representation involves deciding how many bits per color component are required and how to map physical values onto it. First, the ranges of the values which can be assumed by images in each dimension should be established. A good way to do this is by determining the greatest gamut of colors which must be represented and converting it into min and max values along each variable dimension so as to determine a bounding box. Then, a sufficient number of bits should be chosen to quantize each dimension along the range from min to max so that adjacent quantization levels are not distinguishably different in color. Lastly, determine the mapping function from physical onto digital values.

Because the proposed defaults are for Graphic Arts, SC4 has considered the relevant gamuts to be those of color reversal film and photographic paper, the most prevalent inputs. Minority voices on the committee have noted that the era of electronic image capture is at hand and that the gamut of likely environmental colors should be considered. Pointer (1980) has estimated the gamut of real surface colors. In Table One are assembled the limiting a* and b* values for these gamuts. The data on film and paper came from an earlier phase of SC4's work in which Ohta's model (1986) was used to generate the gamut models used to define the IT8.7/1 and /2 targets. Those data consisted of CIELAB maximum Chroma at each of a series of Lightnesses and hue angles, assuming D50 illumination.

TABLE ONE

Coordinates of Bounding Planes, a*, b*

		a*	b*
Film	max	71.41	104.62
	min	- 76.94	- 74.49
Paper	max	70.91	92.97
	min	- 56.73	- 60.35
Pointer	max	81.61	154.96
	min	- 85.35	- 79.05

If the gamut of representation is restricted to film and paper, the range of a* is about +/- 80, while that for b* has been voted to be +120/-80. Assuming ideal perceptual uniformity for CIELAB and 8 bit quantization (255 levels in each dimension) then each level represents 0.63 of a Just Noticeable Difference in a* and 0.78 JND in b*. Quantizing L* over the range 0 to 100 in 8 bits yields 0.39 JND per level in L*. Therefore, 8-bit-per-channel CIELAB is fairly comfortable and image processing systems based on 24-bit CIELUV (1978) (comparable uniformity to CIELAB) have been shown to function largely free of quantization artifacts. Nonetheless, it is tempting to consider a 32 bit CIELAB, in which each pixel would consume one digital long word, employing 10-12 bits of L*, 9 bits each of a* and b* and 2-4 bits of masking weight or translucency. The draft default currently calls for 24 bits, mapping the physical ranges cited onto the range 0 to 255.

It should be noted that this "Graphic Arts CIELAB" is different from TIFF 6.0. The latter employs a default interval for both a* and b* of -127 to +127, and makes no assumption about the illuminant used in the calculations.

TABLE TWO

Coordinates of Bounding Planes, X, Y, Z

		X	Y	Z
Film	max	96.42	100.0	82.49
	min	0.483	1.126	0.326
Paper	max	96.42	100.0	82.49
	min	0.464	0.554	0.476
Pointer	max	96.42	100.0	82.49
	min	0.534	0.554	0.001

In order to estimate bounding box coordinates for XYZ, the CIELAB gamut data described above were converted back to TSVs assuming D50 illumination. Limiting XYZs are reported in Table Two. It is reasonable to consider the working range of the variables based on gamut data to be 0 to 100 along each dimension. The question, then, is how many intervals are needed along each dimension in order to avoid visible quantization. We employed CIELUV color difference calculations to analyze this. Beginning with 255 levels per dimension (8 bits) we took steps in X, Y and Z amounting to a level or some binary fraction thereof. For each step a CIELUV color difference value was calculated and binned. However, the value was binned only if the step took us to a color which fell inside Pointer's gamut. The histogram presented in Figure 8 was based on steps which were one-fourth of an interval; i.e., they corresponded to 10 bit quantization on each dimension. We did not distinguish the dimensions separately in our work and cannot rule out the possibility that different precisions are appropriate for X, Y and Z.

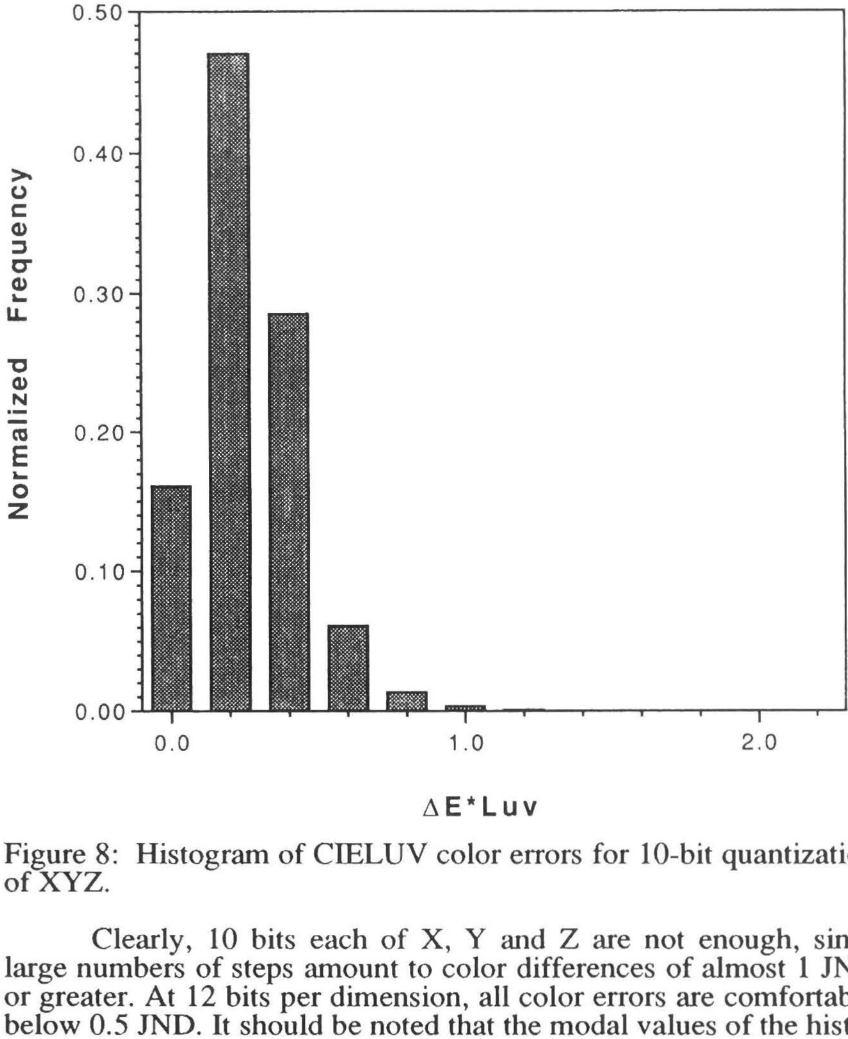


Figure 8: Histogram of CIELUV color errors for 10-bit quantization of XYZ.

Clearly, 10 bits each of X, Y and Z are not enough, since large numbers of steps amount to color differences of almost 1 JND or greater. At 12 bits per dimension, all color errors are comfortably below 0.5 JND. It should be noted that the modal values of the histograms are larger and the upper tails much longer if the restriction that steps lead to a color within Pointer's gamut be dropped. This is true because a cubical quantization scheme for XYZ is rather inefficient and only about 12% of the coordinates in such a scheme are within Pointer's gamut. Admitting the other 90% of coordinates introduces many larger color errors. We are prepared to believe that they are not relevant. At 12 bits per channel, digital XYZ will not fit into a long word and SC4 is now inclined to default to 16 bit-per-channel representation in which the physical range 0 to 1.0 maps onto 0 to 65535 (2^16). D50 illumination would be assumed to underly the computation of the TSVs. Linear transfer or encoding functions are assumed; fewer bits per channel could be used if non-linear encodings were considered. However, the best encodings would result in a notation which approximates CIELAB, which is already one of the proposed defaults.

Summary and Conclusions

1. Largely because of significant differences between the gamut of common display devices and the gamuts of Graphic Arts media, it is not possible to represent the latter with entirely positive values of "calibrated display RGB". In other words, full gamut representation and direct input of the signals to an inexpensive RGB frame buffer are not compatible. Therefore, the draft standard on digital color representations for Graphic Arts applications cannot rely solely on calibrated RGB as a default. A companion paper explains this more fully.

2. The draft standard promotes two other notations, based on the TriStimulus Variables, XYZ, of the CIE's 1931, two-degree Standard Observer and on 1976 CIELAB. These two notations are exact specifications, from a Graphic Arts perspective, of image representations which are more flexibly defined in Aldus' TIFF 6.0 and Adobe's Level II PostScript, two *de facto* standards for handling color images.

3. CIELAB itself embodies a very simple model of chromatic adaptation which guarantees, at the least, that neutrals are properly translated from one viewing condition to another. We evaluated the CIELAB model in comparison with a simple von Kries transformation which could be applied directly to TriStimulus-type spaces without intervention through CIELAB. The two models of white point adjustment were comparable; von Kries involves more computation but has smaller average color errors. Both approaches make errors in hue angle.

4. Eight bits per channel appear to be just sufficient to represent images in CIELAB, at least if the gamuts to be represented are restricted to be those of the common, current Graphic Arts media of film and photographic paper. The quantization intervals of interest are 0 to 100 in L*, -80 to +80 in a* and -80 to +120 in b*. D50 illumination is assumed. In order to represent all the relevant gamuts, the full range of X, Y and Z, from 0 to 1.0 in each dimension is required. At least 11 bits per channel, preferably 12, are required in a uniform quantization scheme to represent the linear variables. Once again, the draft standard assumes TSVs computed for D50.

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