FIRST CONSIDERATIONS OF DEFAULT RGB DATABASE

William C. Kress*

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Abstract: Transmission and reflection test targets enable accurate calibration of input scanning operations. Scanner code values will be easily transformable into tristimulus values (TSVs), or other CIE-based colorimetric number systems. However, displaying TSVs directly on a monitor will result in less than desirable images, in terms of both color and neutrality. Converting TSVs to an RGB database, based on the monitor gamma and the chromaticities of monitor phosphors, will result in good colors within monitor gamut and good neutrals; but any truncation of the resulting negative numbers will cause loss of image detail in highly saturated colors and color shifts. There are several image database alternatives, but no single encoding scheme results in minimal computation time, absence of image artifacts, complete device independence and optimal quantization. This paper discusses some of the possible numerical representations for image data, and their advantages and disadvantages.

Introduction

The IT8.7/1 transmission and IT8.7/2 reflection input scanner test targets specified (ANSI, 1992) by IT8/SC4 and currently available from some photographic manufacturers enable desktop publishing and electronic prepress operations to transform scanned image data to CIE-based colorimetric number systems. There are a number of image encoding schemes enabled by these test targets and members of the IT8/SC4 have been examining alternatives with the goal to define a default RGB database.

This paper will discuss the basic considerations of RGB database design and will address the gamuts of monitors, the derivation and properties of photographic film and paper gamuts and compare these with the gamuts of output

* CalComp, Printer Division, 2411 West La Palma Avenue, Anaheim, CA 92803. 714-821-2867.

materials.

The Gamuts of Color Monitors

To a first approximation, the color gamut obtainable by a monitor can be represented by the area of the chromaticity diagram included within the triangle formed by chromaticities of the red, green and blue phosphors.

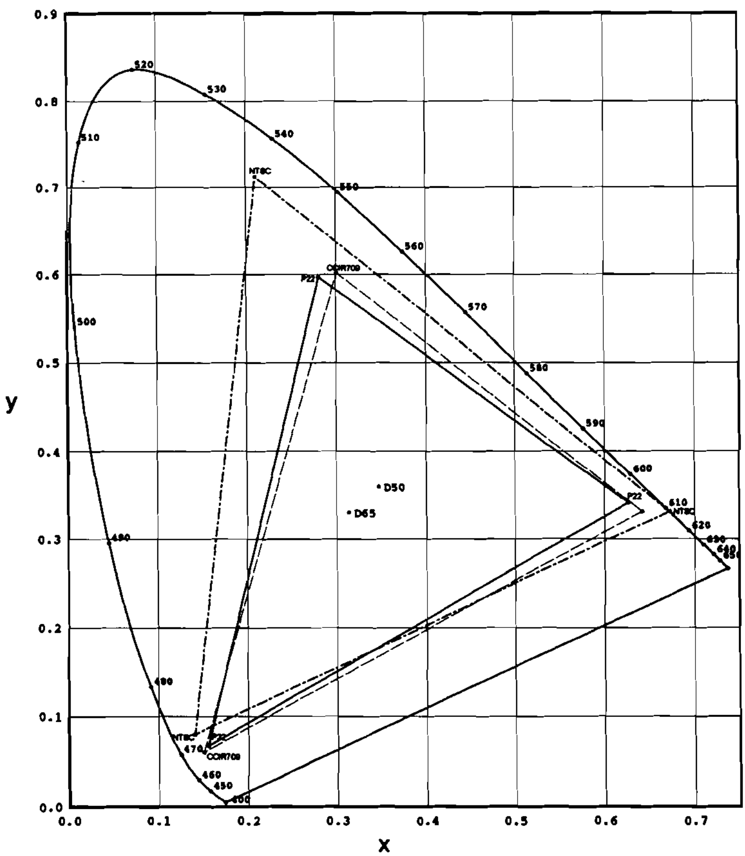

Figure 1. Comparison of CCIR 709, P22 and N.T.S.C. phosphor chromaticities. Note that this is a projection of a three dimensional gamut characteristic.

The following tabulates the nominal values of the chromaticity coordinates of several sets of phosphors that will be used to illustrate the gamuts obtainable with monitors.

	Red		Green		Blue	
	x	y	x	y	x	y
CCIR 709	0.640	0.330	0.300	0.600	0.150	0.060
P22	0.625	0.340	0.280	0.595	0.155	0.070
N.T.S.C.	0.670	0.330	0.210	0.710	0.140	0.080
SMPTE*	0.630	0.340	0.310	0.595	0.155	0.070
D65:	x =	0.3127,	y = 0.3290			

The CCIR 709 phosphors have almost the same chromaticity coordinates as European domestic receivers (Hunt, 1987), and although P22 phosphors are still very much in use, the CCIR 709 may ultimately be the main set. The original N.T.S.C. primaries have quite a wide gamut, but have a lower brightness level than the others, a level probably unacceptable in an office environment. The CIE chromaticity coordinates for the monitor gamuts are shown in Figure 1. SMPTE phosphors are similar to CCIR 709 and P22 and are not shown. An RGB database strictly based on monitor chromaticities will be limited to the projected area within the indicated triangles.

The Gamuts of Photographic Films and Papers

The transmission and reflection input scanner test targets specified by the IT8/SC4 had many patches that were to be colorimetrically common among different product types. This required information about the maximum gamuts of the films and papers from which targets were to be made. The film and paper manufacturers selected six film types and five paper types that were judged representative of products being scanned in the graphic arts/desktop publishing arena. For these films and papers, the combined maximum color gamut in terms of CIELAB data** was estimated. The Appendix lists and Figure 2 plots the data for the combined maximum gamut of six films manufactured by the Agfa Company, Eastman Kodak Company, Fuji Photo Film Company and Konica Corporation.

The methodology by which the film gamuts were determined was a partial photographic system model that manipulated spectral dye amounts. The cyan, magenta, yellow dyes, Dmin (minimum density) spectral characteristics, and maximum status A transmission density of the materials were used. Similarly, the gamut of conventional photographic papers was determined by using the spectral *transmission* characteristics of the cyan, magenta, yellow paper dyes,

* From Society of Motion Picture and Television Engineers, recommended practice, RP 145-1987.

** It was recognized that CIE L* a* b* was defined for reflection materials. However, it did provide a means to exactly specify the required test target's colorimetric characteristics for transmission materials.

reflection Dmin, status A reflection Dmax (maximum density) and a Dr/Dt (transmission to reflection density) transform. Ohta (1972a,b, 1986) describes color gamut calculations in detail. Figure 3 shows the maximum gamuts for both IT8 films and papers on a CIE chromaticity diagram.

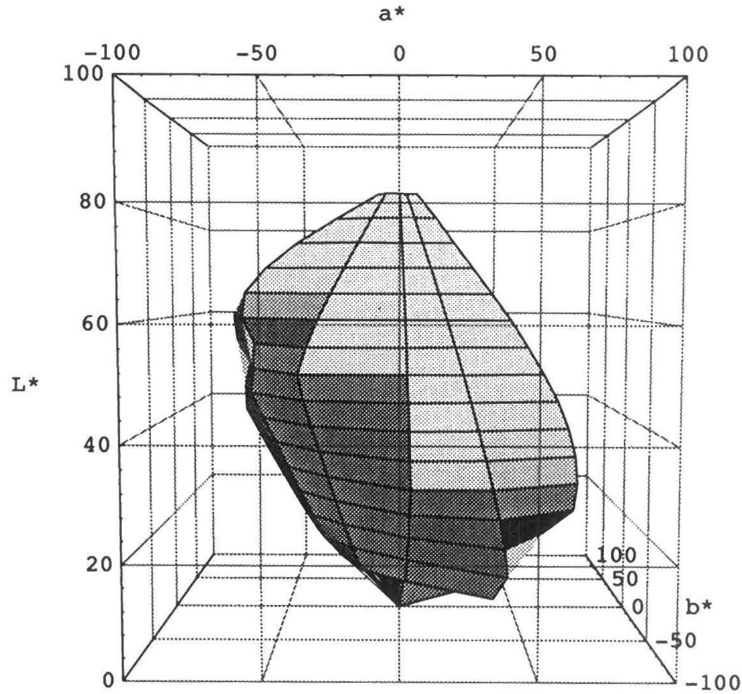

Figure 2. A plot of the data in the Appendix: the maximum gamuts of six IT8 film types in CIE L* a* b* coordinates for D50 illumination. The white reference was the illuminant and film Dmin (minimum density) was between L* of 86 and 89.

At most hue angles, the film gamut exceeded the paper gamut and this showed the dyes', not the systems', capability of achieving this gamut. Reflection measurements of early Agfa IT8 targets and recent measurements of Kodak Q60 targets had suggested the modeled paper gamut to be an overestimate of photographic paper gamut in most regions of color space. Data will be shown in a later Figure illustrating this. It was concluded that the IT8 paper gamuts derived using only a partial system model were not achievable with real products. For films, the questions about the achievable versus modeled gamut were addressed by a verification experiment, which is described in the next section.

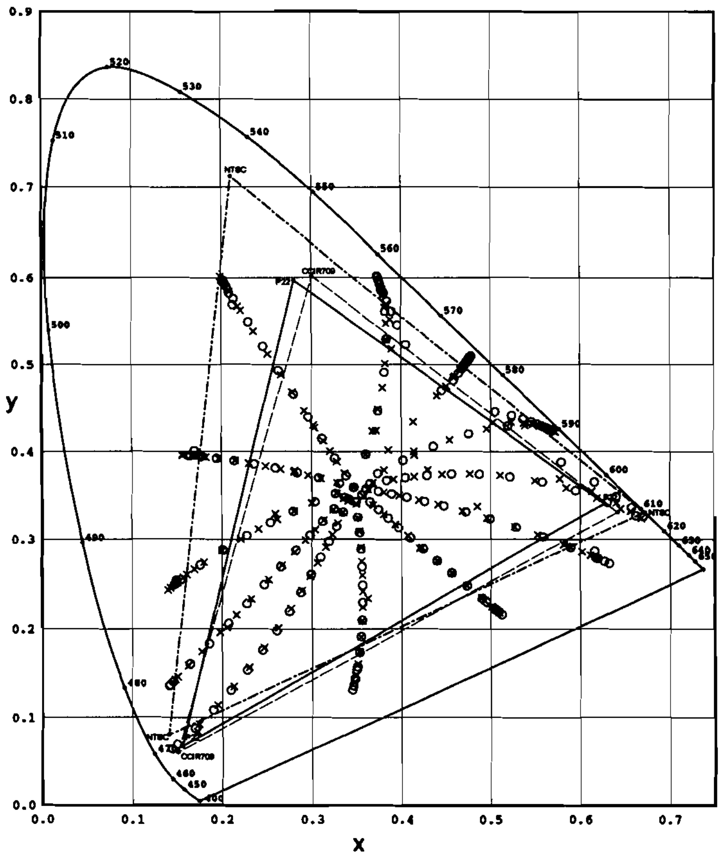

Figure 3. The maximum gamuts of IT8 films (X) and papers (O) for D50 illuminant.

A Gamut Verification Experiment for One Film

The spectral sensitivity, D-Log H curve shape, and the interlayer interimage effects were not included in the gamut calculations and there is potential for these effects to be significant. An experiment was conducted with Kodak Ektachrome 100 film* using an exposure technique that produced the largest possible gamut. Figure 4 shows that the modeled results were an accurate

* Narrow band red, green and blue filters were used to make additive orthogonal step-flash (James, 1977) exposures over a 3.0 log film exposure range. In film building parlance, these are referred to as single-step-double-flash exposures.

predictor in some areas of color space and an overestimate in others.

It was concluded that the IT8 film gamuts were representative of gamuts obtainable by actual films in most regions of color space (except for magenta and cyan) and could be used to estimate the outermost gamuts of photographic products.

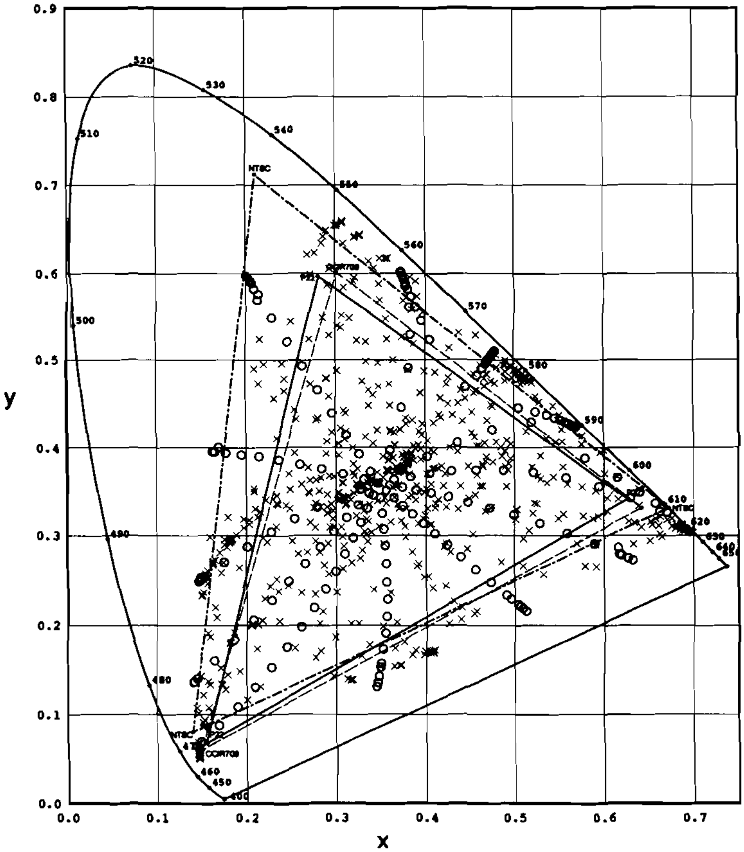

Figure 4. Comparison of modeled (O) versus actual (X) gamut for Kodak Ektachrome 100 film.

Because the default RGB database was intended for the D65 illuminant, and D50 data was available, an illuminant conversion was made. This could have been done quite simply using a von Kries transform. However, one film type, Kodak Kodachrome 64, had the largest gamut in several areas of color space and, as illustrated in Figure 5, had quite different spectral characteristics than the others. A von Kries transform would have applied the same conversion matrix to all films identically, introducing error, so the original dye spectral characteristics were used in a dye matching algorithm to recreate the D50 spectral data at the maximum gamuts, and from this the TSVs for D65 were calculated.

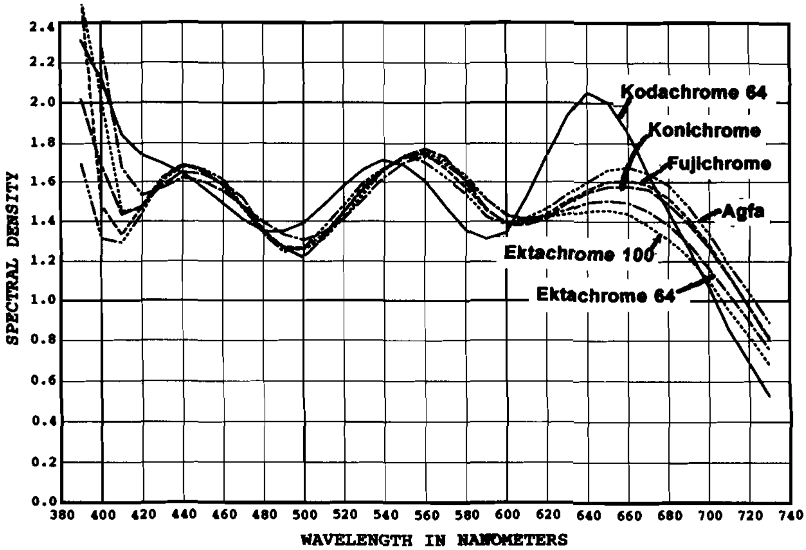

Figure 5. Dye match to L* = 20, a* = b* = 0 using the spectral characteristics of the six IT8 films and D65 illuminant.

Print Material Gamut

Figure 6 shows the gamuts of several print materials as represented by their primary (CMY) and overlay (RGB) colors. Illustrated in this figure are the characteristics from SWOP colorants (samples from International Prepress Association), a standard proofing material (PROOF_A), two dye diffusion thermal transfer medias (D2T2_1,2) and a thermal transfer media (T2). The combined gamut of these materials was quite large. Only the Munsell Limit Color Cascade (not shown) exceeded it slightly in the orange and cyan regions. All the colors producible in film and on the various reflection print materials are not realizable on a CRT, and some colors realizable on a monitor are not realizable on print materials. Note the small gamut of modern CRTs when compared with non SWOP colorants.

A caution should be observed when studying projections of gamuts onto surfaces such as in this Figure. Arrows point to the magenta primaries of SWOP, D2T2_1 and D2T2_2, and show significant hue differences between these colorants. In addition, the D2T2_2 colorant appears to have larger gamut than SWOP and D2T2_1 in the magenta and could easily be used as a prepress proofing media. However, the D2T2_2 magenta primary is considerably darker than SWOP, and increasing its lightness causes desaturation. It turns out that D2T2_2 magenta is only marginally capable of producing SWOP magenta, and D2T2_1 has a magenta that is well beyond the gamut obtainable by both SWOP and D2T2_2 at the L* of 100% SWOP magenta. All gamut analysis should be done using three-dimensional visualization tools as illustrated in Figure 2. Projections have been used herein because of space limitations.

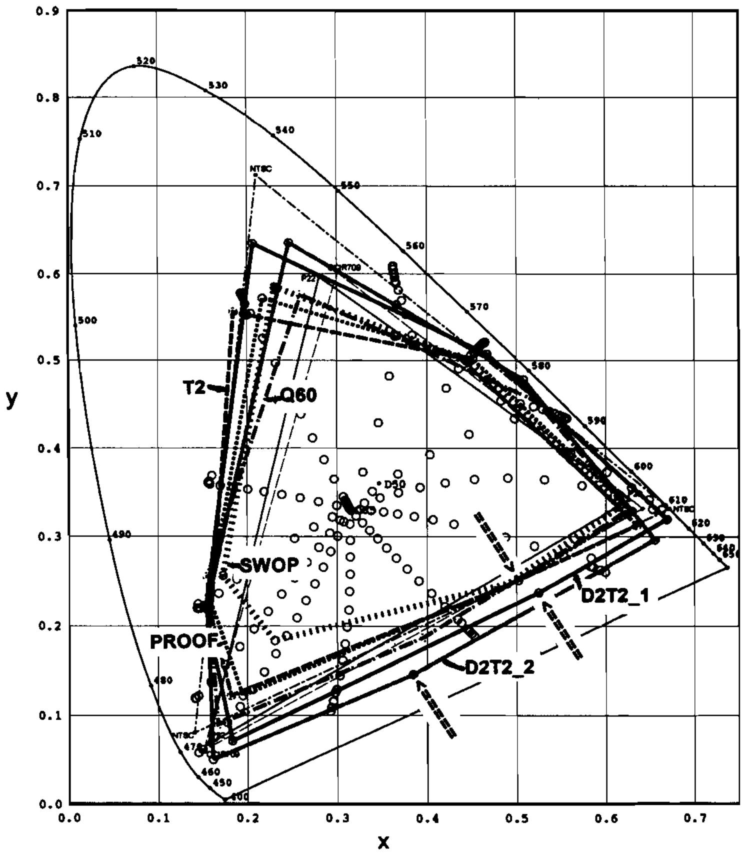

Figure 6. Examples of print gamuts: SWOP, thermal transfer (wax), dye diffusion thermal transfer, Kodak Q60 (Ektacolor Plus Paper) and one graphic arts proofing material. The IT8 film gamut (O) has been included.

Image Data Number System Conversions

Using transmission and reflection test targets defined in IT8.7/1 and 7/2, the relationships between input scanner code values and TSVs can be determined.

The conversion from TSVs into several CIE-related color spaces such as CIELAB and CIELUV can be done. The only transform addressed in detail in this report will be the RGB (Cartesian) coordinate system. There are several conversions that must be considered in the definition of an RGB database:

- Illuminant conversions.*
- Conversion of TSVs to monitor RGB.
- Rescaling to remove colorations in Dmin and Dmax.
- Rescaling to remove media specific levels of Dmin.
- Rescaling to accommodate adaptation and cross rendering limitations.
- Companding (compressing/expanding) the number system to be better aligned with the human visual system.

Conversions of TSVs to monitor RGB

The TSV number system has little meaning when directly displayed on a color monitor. TSVs are linear with respect to visible radiation and require transforms to result in an acceptable display on a color monitor. Furthermore, the TSV neutral scale is not comprised of equal red, green and blue numbers. Figure 7 shows the three-dimensional coverage of IT8 film TSVs, and from this perspective, utilization of the available number system is quite poor.

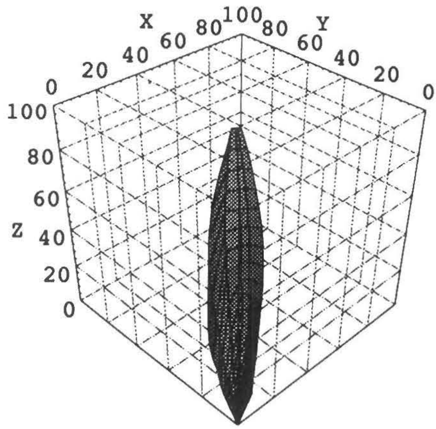

Figure 7. The IT8 film gamut of TSVs, D65 illuminant. The D65 illuminant is 96.0, 100.0, 108.8, and TSVs for Dmin, shown in the table on the previous page, are just beyond the gamut surface toward the top of this Figure.

If the TSVs were multiplied by a matrix related to monitor chromaticities, there would be a considerable expansion to the color space. Equation 1, a TSV (XYZ) to P22 monitor chromaticity (RGB) matrix provides an example of this relationship.

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* Due to lack of space and extensive documentation in the literature, illuminant conversions are not discussed in this paper.

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 2.952 & -1.290 & -0.474 \\ -1.085 & 1.991 & 0.037 \\ 0.085 & -0.269 & 1.091 \end{pmatrix} * \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \qquad (1)$$

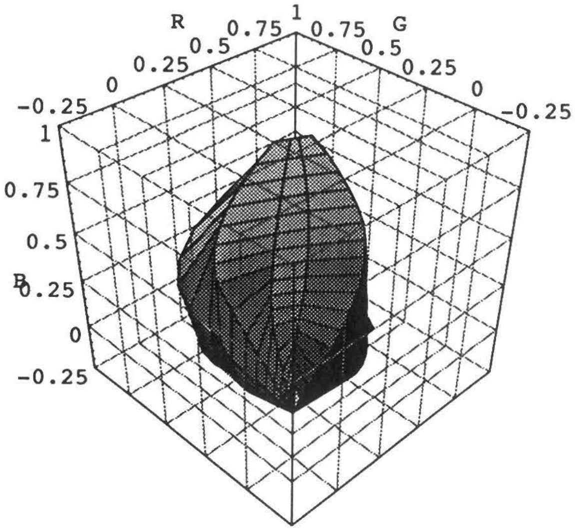

Figure 8. The IT8 film gamut of TSVs after the P22 matrix (see Equation 1). The illuminant has become the point 1.0, 1.0, 1.0 and, compared with Figure 7, the number system has been considerably stretched, generating negative numbers.

Figures 8 and 9 show two perspectives of such a conversion and show that (1) the number system has been significantly expanded, and (2) there are negative numbers. The data would need to be linearized to monitor gamma for accurate color matching. Foley (1990) and Hunt (1987) describe the derivation of TSV to RGB conversions.

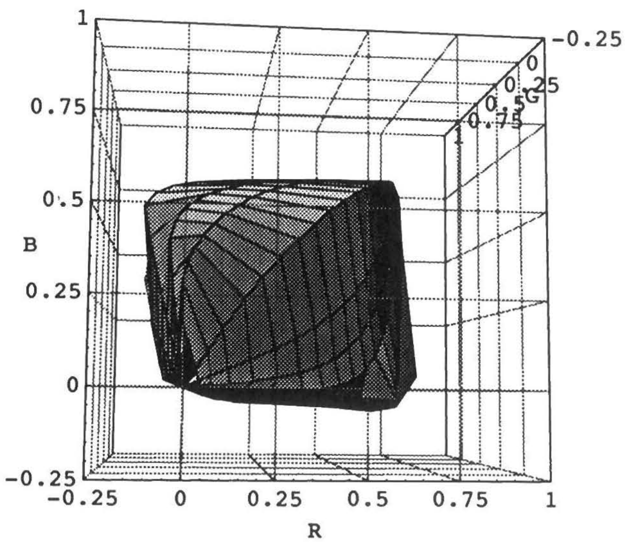

Figure 9. Another perspective of Figure 8 showing the negative numbers that are generated using the XYZ to RGB transform in Equation 1.

If negative numbers were simply truncated, besides a potential loss in image detail, there would be color shifts. The degree of color shift can be simulated by inverting the truncated RGBs through the inverse of Equation 1. Figure 10 illustrates the color shift in a CIE a* versus b* diagram. Similarly, an L* versus c* diagram would show changes in L* because of truncation.

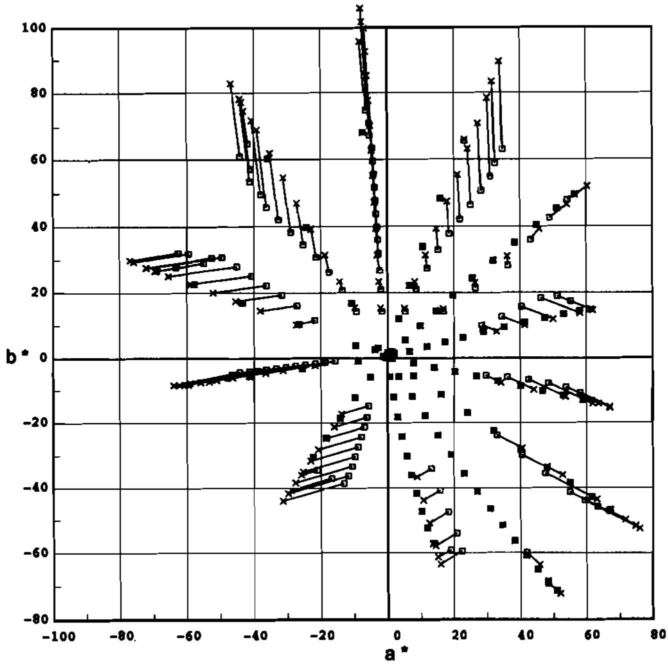

Figure 10. Illustration of the color shifts from of negative number truncation (box) versus non-truncated (X) RGB data (D65, absolute white reference).

Minimum Density – Dmin

The reporting of IT8 target data was done with reference to an absolute white, not the Dmin of the product. It is desirable that the RGB number system not retain any coloration of Dmin and Dmax, and many scanner "acquire" programs permit the removal of these color biases. The TSVs, RGBs for the P22 phosphor set (described in the next section, see Equation 1) and CIE L* a* b* coordinates for the Dmin of the six films, calculated for D65, are listed as follows:

Film	TSVs for D65			RGB for P22			CIELAB		
	X	Y	Z	R	G	B	L*	a*	b*
Agfa	67.8	70.4	74.7	74.0	69.4	68.3	87.2	2.0	1.5
Ekt. 64	64.5	69.7	72.7	66.2	71.5	66.0	86.9	-3.8	2.5
Ekt. 100	71.9	75.0	81.8	76.8	74.3	75.2	89.4	1.4	-0.2
Fuji 100	70.7	74.4	78.9	75.4	74.4	72.0	88.7	0.8	0.2
Kch. 64	64.4	69.1	71.3	67.3	70.3	64.7	86.6	-2.8	3.1
Konica	72.5	75.6	79.7	78.6	74.8	72.8	89.7	1.3	1.9
D65	95.0	100.0	108.8	100.0	100.0	100.0	100.0	0.0	0.0

Depending upon the image, film exposure, lighting, and desired effects by the user, the white reference may be at or close to a specular highlight, and this may be different from Dmin. It is proposed that the white reference of the RGB database should be close to the white reference of input media Dmin or a specular highlight. This is a practical situation in which an optimal image database becomes less related to a CIE specification.

Rescaling to Accommodate Adaptation and Cross Rendering Limitations

All the IT8 films were designed for projected, dark surround viewing. Such viewing conditions reduce the perceived brightness contrasts and require a significantly larger density range to achieve the same appearance as light surround viewing. For example, the maximum status A transmission densities for a film neutral of these films were usually over 3.3. The maximum density for photographic printing (eg., with D2T2_2 media described in a previous section, or with conventional photographic papers) is in the 2.3-2.6 range, and for SWOP printing it is below 2.0. Therefore, rendering across different media with different viewing intentions and maximum density capabilities requires rescaling, and there are a number of ways this can be performed. Appropriate transforms are required and these have been discussed in the literature (Breneman, 1977, and Clapper, 1977).

Companding Functions

A better utilization of the number system is to align the TSV image data with the human visual system. Lindbloom (1989) suggested that a companding function based on the CIE definition of psychometric lightness, applied to each of the RGB channels, would work well. That is, each channel, C_i, of RGB intensities in the range [0, 1] is converted into companded RGB values in the same range as follows:

$$C_c = \begin{cases} 1.16\ (C_i)^{1/3} - 0.16 & \text{for } C_i \geq 0.008856 \\ 9.0329\ (C_i) & \text{for } C_i < 0.008856 \end{cases} \quad (2)$$

Similarly, the Kodak PhotoYCC encoding (Kodak, 1991) used a slightly lower contrast to compand the RGB intensities:

$$C_c = \begin{cases} 1.099\ (C_i)^{0.45} - 0.099 & \text{for } C_i \geq 0.018 \\ 4.50\ (C_i) & \text{for } C_i < 0.018 \end{cases} \quad (3)$$

PhotoYCC preserves the negative numbers, and therefore the gamut, by mirroring the above function about the origin by the following additional definition shown in Equation 4.

$$C_c = \begin{cases} -1.099\ |C_i|^{0.45} + 0.099 & \text{for } C_i \le -0.018 \\ 4.50\ (C_i) & \text{for } -0.018 \le C_i < 0 \end{cases} \quad (4)$$

The high gamma of the companding function required to expand the number system in darker colors is applied to the negative numbers and it is not obvious that this is an optimum use of the available resolution. Figure 11 compares these two companding functions, and the number system range of RGBs after the P22 phosphor matrix is illustrated at the bottom.

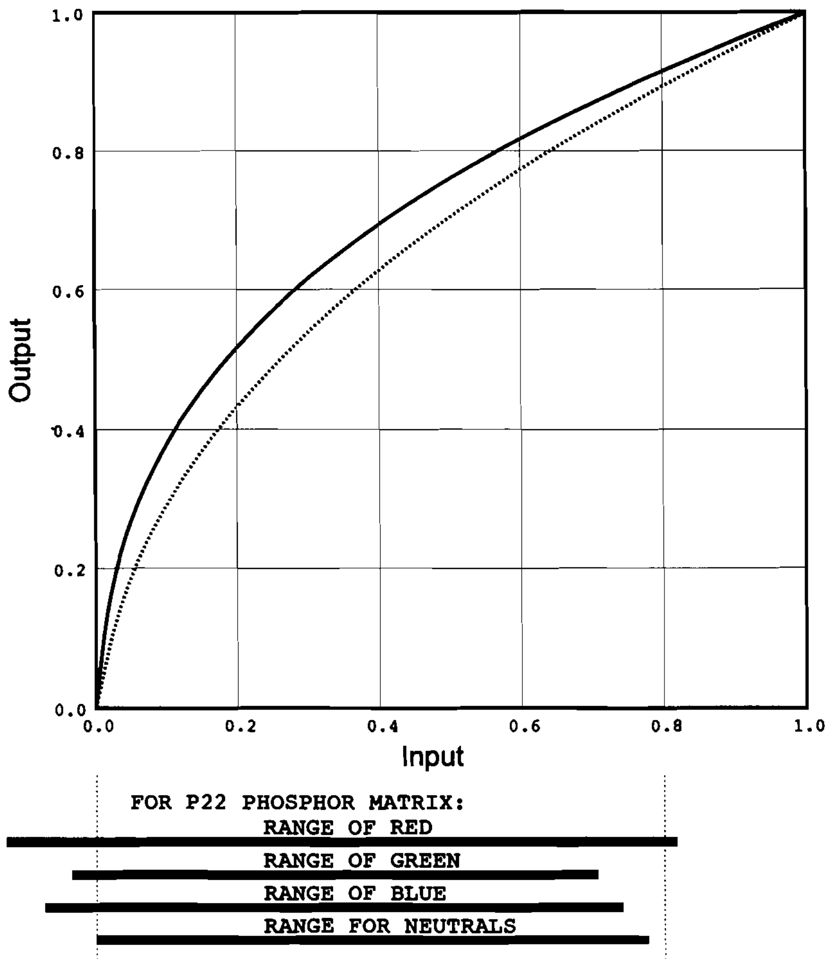

Figure 11. L* (solid) and Kodak PhotoYCC (broken) companding schemes. The range of red, green and blue number system for P22 phosphors is shown underneath.

CRTs are also nonlinear and their gamma (usually calculated by relating the logarithm of the input level with the logarithm of the luminance) is not constant with display luminance. Their gamma differs among devices and their colorimetric output is dependent on phosphor characteristics and ambient illumination. Generally, the type of correction functions required for good monitor display is similar to and approximately between the two companding schemes shown in Figure 11. Many high quality scanners digitize image data in greater than 8-bit per channel resolution and attain satisfactory image quantization by using a companding function similar to those shown in Figure 11 before passing 8-bit per channel data to the host. One of the default databases recommended by IT8/SC4 was monitor RGB image data companded using L* for optimal quantization, and device specific transforms accommodating the range of monitor characteristics could be done in application programs.

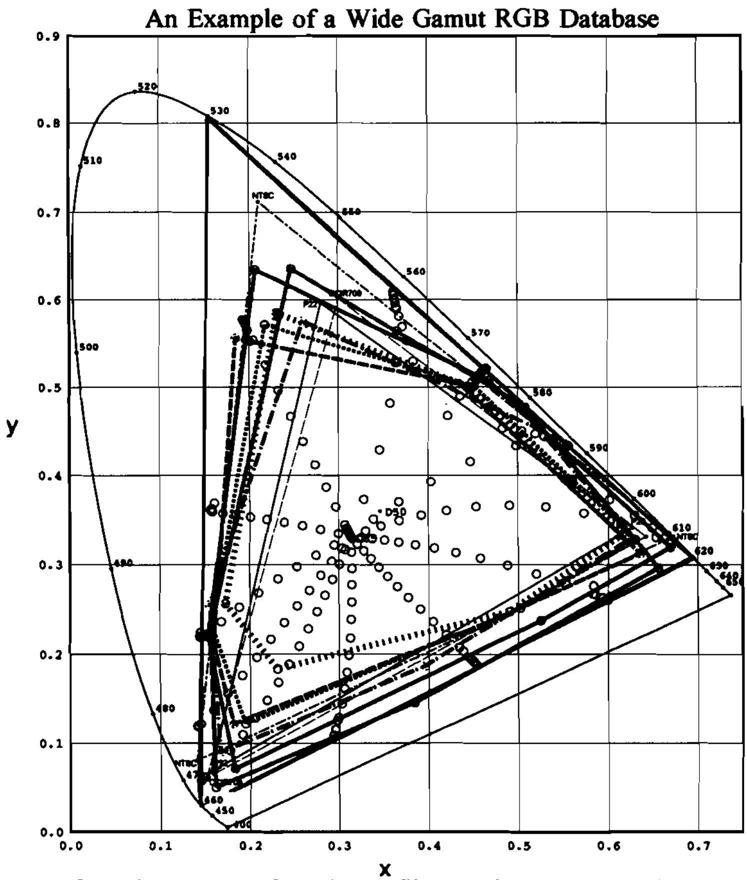

Figure 12. The gamut of all input films and output materials. The large triangle shows the gamut if monochromatic primaries of 620, 530 and 460 nm were used.

An RGB database can be defined in a number of ways as illustrated by the following example. Figure 12 shows all gamuts together on one plot and a large gamut defined by connecting three points on the spectrum locus: the monochromatic illuminants at 620, 530 and 460 nm.

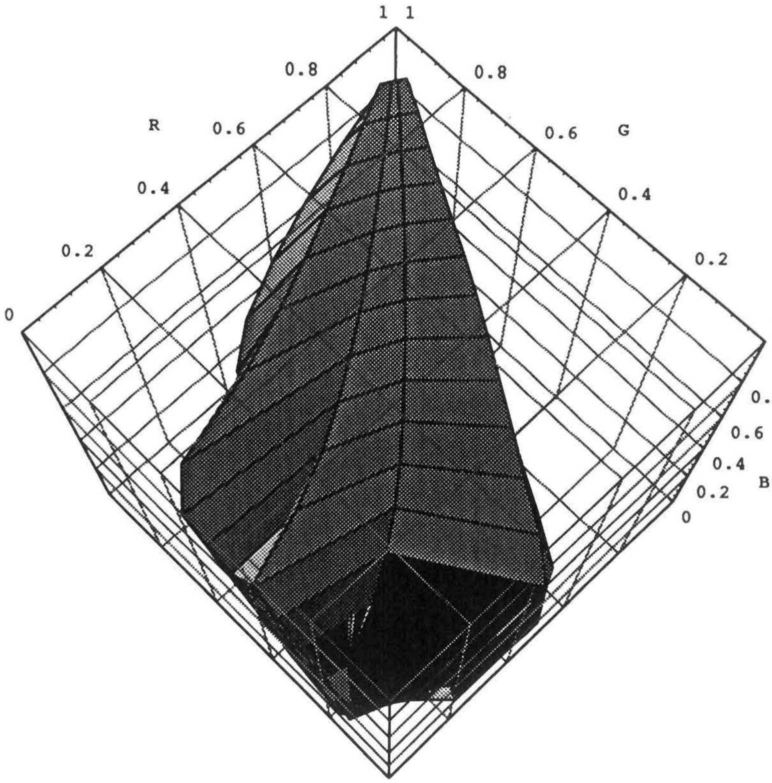

Figure 13. The IT8 film gamut using an RGB color space based on chromaticities at 620, 530 and 460 nm. For this example, the RGB data has been scaled by 1.25 to bring Dmin closer to the 1.0, 1.0, 1.0 point, and then companded using the L* transform of Equation 2.

With this conversion, most of the color gamuts of photographic input materials and output printing products could be encompassed. For these chromaticity coordinates, Equation 5 was derived to convert from TSVs to RGB (both at D65). Figure 13 shows the number system gamut after all the required transforms: multiplication by Equation 5 (any negative numbers were now very close to zero), the RGB rescaled and all positive numbers were mapped through the L* companding function. This is a database representation based on pseudo primaries having significantly larger chromaticities than those for real monitors, and the resulting display will be desaturated. This is not a perceptually uniform color space, such as CIELAB, but is one that is easier to compute for display. Compared with Figure 7 it is a better utilization of the number system and retains a very wide color gamut.

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 1.713 & -0.315 & -0.287 \\ -0.717 & 1.608 & 0.067 \\ 0.022 & -0.050 & 0.945 \end{pmatrix} * \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad (5)$$

It would also be equally reasonable to define the gamut of an RGB image database that would always be printed with the SWOP colorant set to one just bounding the outermost SWOP colors. Using gamut compression to transform out of gamut colors to colors achievable in the printing process may provide sufficient device independence for a particular class of operation.

Summary

There are tradeoffs between quality optimization, device independence and image processing requirements. A well-selected distribution of numbers having 256 discrete levels of three-channel data results in perceptually indistinguishable quantization throughout a very large gamut. Multiple conversions into and out of any color space cause loss in bit resolution. The earlier preparation begins for output rendering--in the input scanner if possible--the lower the likelihood is for visible quantization artifacts.

An RGB database comprised of TSVs is neither a perceptually uniform space nor a good utilization of numbers. It requires matrix expansion, rescaling and companding to generate acceptable images on a CRT, and has unequal red, green, blue numbers for a neutral scale and white point.

An image database that is tied directly to the phosphor chromaticities and, hence, monitor gamut, is device dependent, but (within the gamut) a database colorimetrically related to CIE. It requires rescaling and companding to generate good quality images, and is a better utilization of numbers than a TSV space. If related directly to color monitors' phosphors and gamma, it would require minimal computer processing to display an image. However, monitor RGB is a small color space, smaller than the gamut of conventional photographic input products and smaller in some color regions than the gamuts of output printing systems. Without properly handling gamut mismatches, with simple monitor RGB, there could be objectionable elimination of color detail and shifts in hue, saturation and lightness.

Expanding the monitor RGB database gamut by defining pseudo primaries of greater chromatic strength than obtainable with practically realizable phosphors is another monitor RGB alternative. A much larger database gamut can be retained with this scheme. Depending upon the degree of mismatch between pseudo and real phosphor chromaticities, a matrix may be required for acceptable display and, of course, the resulting *display* cannot represent the entire database color gamut.

The expanded chromaticity coordinate and Kodak PhotoYCC schemes are quite different schemes to handle expanded gamut. They have somewhat lower number system utilization and increased processing requirements than simple monitor RGB. The CIE L* a* b* number system is a good utilization of numbers but is computationally intensive.

The complexity of the considerations for database selection, variations in user computational capabilities and the wide arena of applications suggest that one database metric may not suffice. Accordingly, the current draft of IT8.7/4 defines three default databases: monitor RGB with L* companding, CIELAB and 16-bit TSV.

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APPENDIX

THE MAXIMUM GAMUT OF THE IT8 FILMS -- D50 ILLUMINANT

c* and film type (see key at bottom) for each hue

L*	16		41		67		92		119		161	
10	35.68	3	24.40	2	17.03	2	15.51	2	17.49	2	27.60	3
15	44.67	3	37.44	2	25.96	2	23.56	2	26.50	2	39.13	3
20	53.56	5	50.53	2	34.86	2	31.54	2	35.42	2	47.05	3
25	62.37	3	63.65	2	43.72	2	39.46	2	44.12	2	54.26	3
30	66.37	4	75.32	3	52.51	2	47.27	2	52.67	2	61.47	3
35	66.16	4	83.82	4	61.28	2	55.02	2	60.99	2	68.46	3
40	62.96	4	79.37	4	69.94	2	62.56	2	69.15	2	75.42	3
45	58.15	4	72.72	4	78.50	2	70.08	2	77.08	2	75.82	3
50	52.38	4	64.79	4	86.59	2	77.41	2	79.81	2	73.15	3
55	46.07	4	56.20	4	91.64	3	84.62	2	86.45	3	79.92	5
60	39.47	4	47.50	4	98.05	4	91.71	2	85.42	5	81.37	5
65	32.70	4	38.82	4	72.46	4	98.62	2	91.64	5	73.21	5
70	25.95	4	30.47	6	53.04	4	100.25	3	82.81	5	61.57	5
75	19.88	6	22.89	6	37.31	6	104.68	3	66.94	5	46.19	5
80	13.71	6	15.59	6	24.45	6	94.65	3	44.22	5	28.07	5
85	7.67	6	8.63	6	13.17	6	67.84	3	18.65	4	9.73	4

L*	190		229		274		299		325		350	
10	21.87	6	25.03	3	38.65	3	75.29	3	46.51	5	35.06	3
15	32.97	3	30.75	3	46.14	3	85.17	3	60.28	5	44.69	5
20	38.74	3	35.77	3	53.48	3	83.49	3	72.20	3	54.41	5
25	44.31	3	40.66	3	60.69	3	79.80	3	85.42	3	62.86	3
30	49.71	3	45.47	3	66.35	3	75.32	3	87.17	3	67.87	1
35	55.07	3	50.22	3	63.77	3	70.36	3	86.23	3	68.26	4
40	60.38	3	54.97	3	59.35	3	65.01	3	83.09	3	65.13	4
45	65.55	3	59.58	3	54.19	3	59.31	3	78.15	3	60.47	4
50	64.82	3	62.80	4	48.75	3	53.38	3	71.90	3	54.78	4
55	64.00	5	57.77	3	43.03	3	47.22	3	64.62	3	48.53	4
60	69.34	5	50.97	3	37.18	3	40.86	3	56.69	3	41.80	4
65	67.88	5	43.19	3	31.17	3	34.31	3	47.48	3	34.88	4
70	58.61	5	34.93	3	25.03	3	27.62	3	38.08	3	28.13	6
75	45.12	5	26.43	3	18.84	3	20.79	3	28.80	3	21.49	6
80	27.74	5	17.57	3	12.54	3	13.79	3	19.53	3	14.96	6
85	9.18	4	8.64	3	6.10	3	6.81	3	9.71	3	8.40	6

The film types represented above:

1. Agfa: Agfachrome 100
2. Kodak: Ektachrome 64
3. Kodak: Ektachrome 100
4. Fujichrome 100
5. Kodachrome 64
6. Konicachrome 100