RGB coordinates of the Macbeth ColorChecker

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Abstract. The ColorChecker chart, manufactured by GretagMacbeth, is commonly used as a reference target for photographic and video production work. This document provides RGB coordinates, in 8-bit and 16-bit formats, for all color patches in four common RGB spaces (Adobe, Apple, ProPhoto, and sRGB), which are defined in terms of primaries, Illuminant, and gamma response. The method and equations used to derive the data are presented as well. Reference data provided by the chart's manufacturer is compared to user-measured values.

Subject terms: ColorChecker, RGB coordinates, RGB space, color space, color conversion.

1. Introduction

The ColorChecker[1] chart is ubiquitous in the photographic and video fields. Its main application is for obtaining a rapid assessment of an imaging devices' color rendering accuracy, although it can also be used for simple calibration purposes. The chart consists of 24 color patches formulated to emulate common natural colors such as skin colors, foliage, and sky, in addition to additive and subtractive primaries, and a six steps gray scale[2]. While designed for optimum color consistency when comparing pictures of the chart with pictures of the natural colors, as reproduced on color film, it was shown that the degree of metamerism was also very small when directly comparing the chart to the natural colors.

Until recently, R'G'B' values for this chart were difficult to find. In particular, the R'G'B' data supplied with the chart corresponded to no common RGB space, and no primaries and white point coordinates were provided either. The only official and reliable tristimulus data supplied with the product consisted of xyY coordinates measured with CIE Illuminant C, a common Daylight Illuminant when the original data was measured (from Ref. 2); this data was used, by this author, as a basis to determine R'G'B' values, and published in a previous version of this document. In view of this limited information, the author started, a few years ago, to compile and average spectral data measured on ColorCheckers by users from all over the world. This "real-life" data, from 20 charts of various ages (all of them in well kept conditions), and measured using various instruments, can be seen as an independent validation of the official reference data. This average data, labeled "BabelColor Avg." throughout this text, was used to derive R'G'B' values for comparison purposes. Extracts of the data set are presented here; the complete data is available in a spreadsheet which can be downloaded from the BabelColor Web site[3].

Since about October 2005, the GretagMacbeth Company provides sRGB values, in 8-bit format, and L*a*b* D50 data with its standard size and Mini format ColorChecker charts; the data is also freely accessible on their Web site[4]. The published data is the same for both charts. However, R'G'B' data for other popular spaces, such as Adobe RGB, Apple RGB and ProPhoto, are not given. This paper's purpose is to provide numbers for these spaces, in both 8 bits per primary (24 bits for R'G'B') and 16 bits per primary formats (48 bits for R'G'B'), as well as present the method by which they were derived. These coordinates should be used in any program where specific "RGB" values can be assigned. Please notice the absence of primes against the letters of "RGB" in the preceding sentence, which reflect how gamma corrected coordinates are referred to in most software, even if R'G'B' is the correct form (albeit more cumbersome to write).

However, obtaining R'G'B' data is not enough for many chart users who want to know how representative these numbers are, and how close these numbers are to the ones of their chart. Also, inquisitive users may be interested in how the new numbers compare with the old ones. This is the subject of Section 2. The R'G'B' values derived from the new reference data are presented in Section 3, as well as the R'G'B' values derived from the BabelColor average.

Section 4 presents a short description of each space. The process by which the values were obtained follows, in Section 5. The process can be used for spaces not covered by this paper; for example, for a space defined for a particular display with color primaries different from the ones presented here.

2. Comparing ColorChecker references

We have gathered four data sets which we consider reliable enough to be used as references:

i) ColorChecker 1976: xyY data with Illuminant C (Ref. 2)
ii) ColorChecker 2005: L*a*b* D50 and sRGB (Ref. 4)
iii) BabelColor Avg.: spectral data (Ref. 3)
iv) ProfileMaker 2004: spectral data (2/5/2004)

Other measurements were found, in either tristimulus or spectral form, but they were either incomplete (no data for all patches), or they were from a single chart, or their origin could not be confirmed. We know that, some time ago, L*a*b* D50 data was available from the Munsell Web site, but the file was removed when the Web site was updated.

Table 1a		ColorChecker 2005			ColorChecker 1976			ΔE	
No.	Color name	L*	a*	b*	L*	a*	b*	CIELAB	DE2000
1	dark skin	37,99	13,56	14,06	38,14	13,81	14,75	0,75	0,45
2	light skin	65,71	18,13	17,81	66,63	15,38	17,30	2,95	2,01
3	blue sky	49,93	-4,88	-21,93	50,73	-3,15	-22,43	1,98	1,75
4	foliage	43,14	-13,10	21,91	43,36	-14,99	21,85	1,91	1,32
5	blue flower	55,11	8,84	-25,40	56,01	9,63	-25,74	1,24	0,98
6	bluish green	70,72	-33,40	-0,199	71,50	-31,93	0,831	1,95	1,09
7	orange	62,66	36,07	57,10	62,28	31,88	58,56	4,45	2,72
8	purplish blue	40,02	10,41	-45,96	40,44	11,42	-44,07	2,19	1,61
9	moderate red	51,12	48,24	16,25	51,94	45,25	15,56	3,17	1,26
10	purple	30,33	22,98	-21,59	30,50	23,99	-23,65	2,30	1,06
11	yellow green	72,53	-23,71	57,26	72,83	-23,76	58,64	1,41	0,48
12	orange yellow	71,94	19,36	67,86	72,18	17,40	66,70	2,29	1,08
13	blue	28,78	14,18	-50,30	28,59	20,31	-52,83	6,63	3,11
14	green	55,26	-38,34	31,37	55,66	-38,77	33,09	1,82	0,77
15	red	42,10	53,38	28,19	41,71	53,43	26,98	1,27	0,73
16	yellow	81,73	4,04	79,82	81,95	1,65	78,47	2,75	1,40
17	magenta	51,94	49,99	-14,57	51,57	48,99	-15,57	1,46	0,72
18	cyan	51,04	-28,63	-28,64	51,07	-28,01	-27,36	1,42	0,54
19	white 9.5 (.05 D)	96,54	-0,425	1,186	96,00	-0,062	0,067	1,29	1,25
20	neutral 8 (.23 D)	81,26	-0,638	-0,335	81,35	-0,054	0,058	0,71	0,94
21	neutral 6.5 (.44 D)	66,77	-0,734	-0,504	66,67	-0,046	0,049	0,89	1,14
22	neutral 5 (.70 D)	50,87	-0,153	-0,270	51,58	-0,037	0,040	0,78	0,79
23	neutral 3.5 (1.05 D)	35,66	-0,421	-1,231	35,99	-0,029	0,031	1,36	1,38
24	black 2 (1.5 D)	20,46	-0,079	-0,973	20,56	-0,020	0,022	1,00	0,98
							avg. :	2,00	1,23

ΔE
ΔE ≤ 1
1 < ΔE ≤ 2
2 < ΔE ≤ 4
4 < ΔE

Table 1b		ColorChecker 2005			BabelColor Avg.			ΔE	
No.	Color name	L*	a*	b*	L*	a*	b*	CIELAB	DE2000
1	dark skin	37,99	13,56	14,06	38,36	13,80	14,65	0,74	0,49
2	light skin	65,71	18,13	17,81	66,06	17,74	17,85	0,52	0,40
3	blue sky	49,93	-4,88	-21,93	50,09	-4,41	-22,51	0,77	0,50
4	foliage	43,14	-13,10	21,91	43,20	-13,46	21,73	0,41	0,31
5	blue flower	55,11	8,84	-25,40	55,36	8,89	-24,82	0,63	0,46
6	bluish green	70,72	-33,40	-0,199	70,70	-32,89	-0,240	0,51	0,21
7	orange	62,66	36,07	57,10	62,56	35,13	58,05	1,34	0,80
8	purplish blue	40,02	10,41	-45,96	40,18	9,55	-44,29	1,89	0,39
9	moderate red	51,12	48,24	16,25	51,71	47,69	16,86	1,01	0,73
10	purple	30,33	22,98	-21,59	30,38	21,13	-20,31	2,24	0,97
11	yellow green	72,53	-23,71	57,26	72,49	-23,46	57,08	0,31	0,11
12	orange yellow	71,94	19,36	67,86	71,96	19,49	68,00	0,19	0,07
13	blue	28,78	14,18	-50,30	28,65	15,60	-50,52	1,44	0,88
14	green	55,26	-38,34	31,37	55,05	-38,09	31,62	0,41	0,27
15	red	42,10	53,38	28,19	42,18	54,89	28,79	1,63	0,45
16	yellow	81,73	4,04	79,82	82,23	4,05	79,84	0,50	0,34
17	magenta	51,94	49,99	-14,57	51,82	49,79	-13,90	0,71	0,32
18	cyan	51,04	-28,63	-28,64	50,55	-27,97	-28,14	0,96	0,57
19	white 9.5 (.05 D)	96,54	-0,425	1,186	96,39	-0,404	2,238	1,06	0,98
20	neutral 8 (.23 D)	81,26	-0,638	-0,335	81,01	-0,570	0,180	0,57	0,54
21	neutral 6.5 (.44 D)	66,77	-0,734	-0,504	66,30	-0,434	-0,079	0,70	0,71
22	neutral 5 (.70 D)	50,87	-0,153	-0,270	50,83	-0,687	-0,268	0,54	0,78
23	neutral 3.5 (1.05 D)	35,66	-0,421	-1,231	35,72	-0,521	-0,468	0,77	0,75
24	black 2 (1.5 D)	20,46	-0,079	-0,973	20,71	0,025	-0,447	0,59	0,56
							avg. :	0,85	0,52

Table 1a: Official L*a*b* D50 values of the ColorChecker, as made available by GretagMacbeth in 2005 ("ColorChecker 2005"), compared to the previously distributed data measured in 1976 ("ColorChecker 1976"). The 1976 data, measured with Illuminant C, was converted to Illuminant D50 using a Bradford chromatic adaptation transform.
Table 1b: "ColorChecker 2005" data compared to L*a*b* D50 data derived from the average of 20 charts compiled by BabelColor ("BabelColor Avg.").

Table 1c		ColorChecker 2005			ProfileMaker 2004			ΔE	
No.	Color name	L*	a*	b*	L*	a*	b*	CIELAB	DE2000
1	dark skin	37,99	13,56	14,06	38,40	13,58	14,52	0,62	0,47
2	light skin	65,71	18,13	17,81	66,07	18,02	18,22	0,56	0,43
3	blue sky	49,93	-4,88	-21,93	50,17	-4,91	-21,70	0,33	0,27
4	foliage	43,14	-13,10	21,91	43,27	-13,33	22,67	0,81	0,40
5	blue flower	55,11	8,84	-25,40	55,47	8,84	-25,14	0,45	0,38
6	bluish green	70,72	-33,40	-0,199	71,23	-33,03	-0,060	0,65	0,43
7	orange	62,66	36,07	57,10	62,83	35,88	58,29	1,22	0,55
8	purplish blue	40,02	10,41	-45,96	40,27	10,39	-45,87	0,27	0,23
9	moderate red	51,12	48,24	16,25	51,26	48,01	16,56	0,41	0,26
10	purple	30,33	22,98	-21,59	30,47	21,07	-21,28	1,94	1,03
11	yellow green	72,53	-23,71	57,26	72,95	-23,45	57,89	0,80	0,43
12	orange yellow	71,94	19,36	67,86	72,27	19,25	68,94	1,14	0,42
13	blue	28,78	14,18	-50,30	28,71	14,36	-50,02	0,34	0,25
14	green	55,26	-38,34	31,37	55,40	-38,02	32,01	0,73	0,37
15	red	42,10	53,38	28,19	41,50	56,42	28,41	3,11	1,14
16	yellow	81,73	4,04	79,82	82,56	3,49	80,85	1,43	0,69
17	magenta	51,94	49,99	-14,57	52,20	49,90	-14,30	0,39	0,29
18	cyan	51,04	-28,63	-28,64	51,37	-28,48	-28,29	0,51	0,36
19	white 9.5 (.05 D)	96,54	-0,425	1,186	96,96	-0,474	1,470	0,51	0,37
20	neutral 8 (.23 D)	81,26	-0,638	-0,335	81,57	-0,703	0,097	0,54	0,49
21	neutral 6.5 (.44 D)	66,77	-0,734	-0,504	67,17	-0,779	-0,083	0,58	0,53
22	neutral 5 (.70 D)	50,87	-0,153	-0,270	50,15	-1,225	-0,490	1,31	1,71
23	neutral 3.5 (1.05 D)	35,66	-0,421	-1,231	35,94	-0,336	-0,741	0,58	0,54
24	black 2 (1.5 D)	20,46	-0,079	-0,973	20,38	-0,360	-0,365	0,68	0,73
							avg. :	0,83	0,53

ΔE
ΔE ≤ 1
1 < ΔE ≤ 2
2 < ΔE ≤ 4
4 < ΔE

Table 1d		BabelColor Avg.			ProfileMaker 2004			ΔE	
No.	Color name	L*	a*	b*	L*	a*	b*	CIELAB	DE2000
1	dark skin	38,36	13,80	14,65	38,40	13,58	14,52	0,26	0,17
2	light skin	66,06	17,74	17,85	66,07	18,02	18,22	0,47	0,23
3	blue sky	50,09	-4,41	-22,51	50,17	-4,91	-21,70	0,95	0,55
4	foliage	43,20	-13,46	21,73	43,27	-13,33	22,67	0,95	0,55
5	blue flower	55,36	8,89	-24,82	55,47	8,84	-25,14	0,34	0,26
6	bluish green	70,70	-32,89	-0,240	71,23	-33,03	-0,060	0,58	0,43
7	orange	62,56	35,13	58,05	62,83	35,88	58,29	0,83	0,41
8	purplish blue	40,18	9,55	-44,29	40,27	10,39	-45,87	1,79	0,35
9	moderate red	51,71	47,69	16,86	51,26	48,01	16,56	0,62	0,50
10	purple	30,38	21,13	-20,31	30,47	21,07	-21,28	0,98	0,61
11	yellow green	72,49	-23,46	57,08	72,95	-23,45	57,89	0,93	0,43
12	orange yellow	71,96	19,49	68,00	72,27	19,25	68,94	1,02	0,43
13	blue	28,65	15,60	-50,52	28,71	14,36	-50,02	1,33	0,65
14	green	55,05	-38,09	31,62	55,40	-38,02	32,01	0,53	0,38
15	red	42,18	54,89	28,79	41,50	56,42	28,41	1,72	0,90
16	yellow	82,23	4,05	79,84	82,56	3,49	80,85	1,20	0,47
17	magenta	51,82	49,79	-13,90	52,20	49,90	-14,30	0,56	0,41
18	cyan	50,55	-27,97	-28,14	51,37	-28,48	-28,29	0,97	0,85
19	white 9.5 (.05 D)	96,39	-0,404	2,238	96,96	-0,474	1,470	0,96	0,80
20	neutral 8 (.23 D)	81,01	-0,570	0,180	81,57	-0,703	0,097	0,58	0,44
21	neutral 6.5 (.44 D)	66,30	-0,434	-0,079	67,17	-0,779	-0,083	0,94	0,86
22	neutral 5 (.70 D)	50,83	-0,687	-0,268	50,15	-1,225	-0,490	0,89	1,04
23	neutral 3.5 (1.05 D)	35,72	-0,521	-0,468	35,94	-0,336	-0,741	0,40	0,42
24	black 2 (1.5 D)	20,71	0,025	-0,447	20,38	-0,360	-0,365	0,51	0,62
							avg. :	0,85	0,53

Table 1c: Official L*a*b* D50 values of the ColorChecker, as made available by GretagMacbeth in 2005 ("ColorChecker 2005"), compared to values derived from the reference spectral file provided with ProfileMaker ("ProfileMaker 2004"; file name: "ColorChecker 24"; file measurement date: "2/5/2004").
Table 1d: L*a*b* D50 data derived from the average of 20 charts compiled by BabelColor ("BabelColor Avg."), compared to "ProfileMaker 2004".

The first comparison that comes to mind is the one between the two "official" tristimulus data sets, published in 1976 ("ColorChecker 1976") and 2005 ("ColorChecker 2005"), shown in Table 1a. In order to compare the two sets on the same basis, we have chosen to convert the xyY Ill-C (1976) coordinates to the L*a*b* D50 color space used for the most recent reference. From xyY, one can readily determine XYZ values, then use a Chromatic Adaptation Transform (CAT), in this case the Bradford matrix discussed in Section 5.2, to convert the XYZ coordinates between Illuminant C and Illuminant D50, and finally compute the proper L*a*b* values. The use of a CAT is required since we do not have the spectral data corresponding to the xyY coordinates. While using a CAT can introduce an error, this error has less of an effect than if it was simply added to the inherent difference between the data sets; see Section 6 for more information.

The second comparison, shown in Table 1b, is between the "ColorChecker 2005" data set and the "BabelColor Avg.". The third comparison, Table 1c, is between the "ColorChecker 2005" set and tristimulus data derived from a spectral reference file of the ColorChecker (ProfileMaker 2004). This file is provided by GretagMacbeth as part of their ProfileMaker software package; the measurement date shown in the file is "2/5/2004". The fourth comparison, Table 1d, is between the "BabelColor Avg." and "ProfileMaker 2004" data sets.

The color differences in Table 1 are computed using both CIELAB and CIEDE2000. CIEDE2000 is the most recent color difference formula recommended by the Commission Internationale de l'Éclairage (CIE). Like the CIE94 and CMC color difference formulas which came after CIELAB, it strives to improve the match between the perceived color difference and the computed difference values. CIEDE2000, similarly to the CIE94 and CMC formulas, includes weighting functions for lightness, chroma and hue. However, it introduces an extra term which combines chroma and hue with the goal of improving the performance for blue colors (for hue angles – the h* in the L*C*h* presentation format – around 275 degrees). It also associates a scaling factor to a* for low chroma colors, to improve the formula performance near the illuminant. Many users have confirmed that CIEDE2000, while still not perfect, does achieve its goal of improving the match between computed difference numbers and perceived difference[5].

In Table 1a, we see a noticeable difference between the "ColorChecker 1976" and "ColorChecker 2005" data sets, whereas the difference is quite small when comparing the 2005 data with either the "BabelColor Avg." or the "ProfileMaker 2004" sets in Tables 1b and 1c. The 1976 data may have been deemed sufficiently precise at a time where the chart was mostly used to visually judge the quality of silver-based films, and not used to make precise digital measurements as we do now.

As per GretagMacbeth Web site, the 2005 ColorChecker data "*is intended to be an average measurement of all ColorChecker Charts*". The fact that, on average, this data set cannot be visually differentiated from either the "ProfileMaker 2004" or the "BabelColor Avg." data sets makes it difficult to select the best one. There is no detailed information on where the 2005 data comes from; it may be an average from one, or from many production lots. There is even less information on the origin of the ProfileMaker reference file but its good match to the other data sets indicates it is also an average of some sorts. As for the data compiled by BabelColor, the match to the other two data sets is quite good, especially considering the mix of experimental conditions imposed by many users using different instruments. Overall, the similarity of the three data sets points to some outstanding long term production consistency.

Readers interested in seeing spectral graphs for each patch, as well as information on spectral and L*a*b* variance, can download the "ColorChecker_RGB_and_spectra.xls" spreadsheet from the BabelColor Web site (see Ref. 3).

3. RGB coordinates of the ColorChecker

The R'G'B' values of the ColorChecker for four common RGB spaces, Adobe, Apple, ProPhoto and sRGB, are shown in 8-bit format in Table 2, and in 16-bit format in Table 3.

Table 3 is a more precise version of Table 2, with more significant digits per value. The 16-bit values can be used mainly in programming environments, such as MATLAB, since there is no color picker that yet offers 16-bit resolution. You should be aware that, for computing efficiency reasons, Photoshop processes 16-bit file as if 15-bit and resaves the file as 16-bit; the displayed color numbers are thus divided by two from the 16-bit values.

In Tables 2 and 3, the tables labeled "ColorChecker 2005" show the L*a*b* D50 values provided by GretagMacbeth. You will notice two columns with sRGB in their title in Table 2; the one labeled "sRGB (GMB)" contains the values provided by GretagMacbeth, while the "sRGB" column was derived from L*a*b* D50 using the procedure presented in Section 5. The other R'G'B' values of the "ColorChecker 2005" table were derived in a similar manner. It should be emphasized that for ProPhoto, a D50 based RGB space, there is no need to perform a chromatic adaptation transform when starting with L*a*b* D50 and that there is minimal "conversion process-induced" errors (see Section 6).

All R'G'B' values of the "BabelColor Avg." tables were obtained with the spectral reflectance average of 20 charts, the space Illuminant spectral distribution, and the 2-degrees Standard Observer. In other words, they were not obtained using a chromatic adaptation transform, and do not comprise the errors this transform may introduce.

It is interesting to note in Table 2 that the "sRGB (GMB)" cyan patch is measured to be within the sRGB gamut, with an R' value of 8, while this coordinate is clipped to zero when derived from the L*a*b* data (as can be seen in the "sRGB" column of the "ColorChecker 2005" table). The cyan is similarly clipped in the "BabelColor Avg." tables.

ColorChecker 2005		xyY (CIE D50)			L*a*b* (CIE D50)			Adobe			Apple			ProPhoto			sRGB			sRGB (GMB)		
No.	**Color name**	**x**	**y**	**Y**	**L***	**a***	**b***	**R'**	**G'**	**B'**	**R'**	**G'**	**B'**	**R'**	**G'**	**B'**	**R'**	**G'**	**B'**	**R'**	**G'**	**B'**
0	**illuminant**	**0,3457**	**0,3585**	**100**	**100**	**0**	**0**	**255**	**255**	**255**	**255**	**255**	**255**	**255**	**255**	**255**	**255**	**255**	**255**	**255**	**255**	**255**
1	**dark skin**	0,4316	0,3777	10,08	37,99	13,56	14,06	107	82	70	94	63	51	81	67	54	116	81	67	115	82	68
2	**light skin**	0,4197	0,3744	34,95	65,71	18,13	17,81	184	146	129	183	128	109	159	135	114	199	147	129	194	150	130
3	**blue sky**	0,2760	0,3016	18,36	49,93	-4,88	-21,93	101	122	153	74	103	139	94	102	133	91	122	156	98	122	157
4	**foliage**	0,3703	0,4499	13,25	43,14	-13,10	21,91	95	107	69	73	89	48	75	86	55	90	108	64	87	108	67
5	**blue flower**	0,2999	0,2856	23,04	55,11	8,84	-25,40	128	127	173	110	108	162	118	111	154	130	128	176	133	128	177
6	**bluish green**	0,2848	0,3911	41,78	70,72	-33,40	-0,20	129	188	171	84	178	155	127	168	157	92	190	172	103	189	170
7	**orange**	0,5295	0,4055	31,18	62,66	36,07	57,10	201	123	56	211	102	30	167	118	54	224	124	47	214	126	44
8	**purplish blue**	0,2305	0,2106	11,26	40,02	10,41	-45,96	77	92	166	52	71	156	79	74	145	68	91	170	80	91	166
9	**moderate red**	0,5012	0,3273	19,38	51,12	48,24	16,25	174	83	97	180	59	79	141	83	80	198	82	97	193	90	99
10	**purple**	0,3319	0,2482	6,37	30,33	22,98	-21,59	86	61	104	73	42	88	68	49	82	94	58	106	94	60	108
11	**yellow green**	0,3984	0,5008	44,46	72,53	-23,71	57,26	167	188	75	145	177	39	144	170	74	159	189	63	157	188	64
12	**orange yellow**	0,4957	0,4427	43,57	71,94	19,36	67,86	213	160	55	220	143	19	181	152	60	230	162	39	224	163	46
13	**blue**	0,2018	0,1692	5,75	28,78	14,18	-50,30	49	65	143	26	47	131	57	50	120	35	63	147	56	61	150
14	**green**	0,3253	0,5032	23,18	55,26	-38,34	31,37	99	148	80	60	133	54	85	123	69	67	149	74	70	148	73
15	**red**	0,5686	0,3303	12,57	42,10	53,38	28,19	155	52	59	159	29	43	120	59	46	180	49	57	175	54	60
16	**yellow**	0,4697	0,4734	59,81	81,73	4,04	79,82	227	197	52	232	187	0	199	188	66	238	198	20	231	199	31
17	**magenta**	0,4159	0,2688	20,09	51,94	49,99	-14,57	169	85	147	174	60	134	143	85	127	193	84	151	187	86	149
18	**cyan**	0,2131	0,3023	19,30	51,04	-28,63	-28,64	61	135	167	0	118	154	78	111	148	0	136	170	8	133	161
19	**white 9.5 (.05 D)**	0,3469	0,3608	91,31	96,54	-0,43	1,19	245	245	242	242	243	239	242	243	240	245	245	243	243	243	242
20	**neutral 8 (.23 D)**	0,3440	0,3584	58,94	81,26	-0,64	-0,34	200	201	201	189	191	191	189	190	191	200	202	202	200	200	200
21	**neutral 6.5 (.44 D)**	0,3432	0,3581	36,32	66,77	-0,73	-0,50	160	161	162	144	146	146	145	146	146	161	163	163	160	160	160
22	**neutral 5 (.70 D)**	0,3446	0,3579	19,15	50,87	-0,15	-0,27	120	120	121	101	102	102	102	102	102	121	121	122	122	122	121
23	**neutral 3.5 (1.05 D)**	0,3401	0,3548	8,83	35,66	-0,42	-1,23	84	85	86	65	66	68	66	66	68	82	84	86	85	85	85
24	**black 2 (1.5 D)**	0,3406	0,3537	3,11	20,46	-0,08	-0,97	52	53	54	37	37	38	37	37	38	49	49	51	52	52	52

BabelColor Avg.		xyY (CIE D50)			L*a*b* (CIE D50)			Adobe			Apple			ProPhoto			sRGB		
No.	**Color name**	**x**	**y**	**Y**	**L***	**a***	**b***	**R'**	**G'**	**B'**	**R'**	**G'**	**B'**	**R'**	**G'**	**B'**	**R'**	**G'**	**B'**
0	**illuminant**	**0,3457**	**0,3585**	**100**	**100**	**0**	**0**	**255**	**255**	**255**	**255**	**255**	**255**	**255**	**255**	**255**	**255**	**255**	**255**
1	**dark skin**	0,4336	0,3787	10,29	38,36	13,80	14,65	107	82	70	94	63	51	82	68	54	115	81	67
2	**light skin**	0,4187	0,3749	35,40	66,06	17,74	17,85	182	148	129	180	130	109	160	136	114	196	149	129
3	**blue sky**	0,2757	0,2996	18,49	50,09	-4,41	-22,51	103	122	155	76	103	141	95	102	135	93	123	157
4	**foliage**	0,3688	0,4501	13,29	43,20	-13,46	21,73	96	108	69	73	90	48	75	86	56	90	108	65
5	**blue flower**	0,3016	0,2871	23,28	55,36	8,89	-24,82	129	128	173	110	108	162	119	111	154	130	129	176
6	**bluish green**	0,2856	0,3905	41,75	70,70	-32,89	-0,24	132	189	170	89	179	154	127	168	157	99	191	171
7	**orange**	0,5291	0,4081	31,06	62,56	35,13	58,05	197	122	54	206	101	29	166	118	52	220	123	45
8	**purplish blue**	0,2335	0,2157	11,36	40,18	9,55	-44,29	79	92	164	55	72	153	79	75	143	72	92	168
9	**moderate red**	0,5002	0,3295	19,89	51,71	47,69	16,86	171	85	97	176	62	79	142	85	80	195	84	98
10	**purple**	0,3316	0,2544	6,39	30,38	21,13	-20,31	84	61	103	70	43	87	67	50	81	91	59	105
11	**yellow green**	0,3986	0,5002	44,40	72,49	-23,46	57,08	168	188	75	147	177	38	144	169	74	160	189	62
12	**orange yellow**	0,4960	0,4426	43,60	71,96	19,49	68,00	211	159	56	218	142	20	182	152	60	229	161	41
13	**blue**	0,2042	0,1676	5,70	28,65	15,60	-50,52	53	64	143	32	45	131	57	50	120	43	62	147
14	**green**	0,3262	0,5040	22,97	55,05	-38,09	31,62	101	148	78	63	133	52	85	122	68	71	149	72
15	**red**	0,5734	0,3284	12,62	42,18	54,89	28,79	151	52	59	154	29	43	121	59	46	176	48	56
16	**yellow**	0,4693	0,4730	60,72	82,23	4,05	79,84	227	198	53	232	188	0	201	190	67	238	200	22
17	**magenta**	0,4175	0,2702	19,98	51,82	49,79	-13,90	165	85	147	168	60	133	143	85	126	188	84	150
18	**cyan**	0,2146	0,3028	18,89	50,55	-27,97	-28,14	65	135	164	0	118	151	77	109	146	0	136	166
19	**white 9.5 (.05 D)**	0,3486	0,3625	90,94	96,39	-0,40	2,24	245	245	240	243	242	236	242	242	237	245	245	240
20	**neutral 8 (.23 D)**	0,3451	0,3593	58,50	81,01	-0,57	0,18	199	200	199	188	190	189	189	190	189	200	201	201
21	**neutral 6.5 (.44 D)**	0,3447	0,3588	35,71	66,30	-0,43	-0,08	159	160	160	143	144	144	144	144	144	160	161	161
22	**neutral 5 (.70 D)**	0,3433	0,3586	19,12	50,83	-0,69	-0,27	119	121	121	101	102	102	101	102	102	120	121	121
23	**neutral 3.5 (1.05 D)**	0,3425	0,3577	8,87	35,72	-0,52	-0,47	84	85	85	66	67	67	66	67	67	83	84	85
24	**black 2 (1.5 D)**	0,3436	0,3562	3,17	20,71	0,03	-0,45	53	53	54	37	37	38	37	37	38	50	50	50

Table 2: R'G'B' coordinates of the ColorChecker, in **8-bit** format. Coordinates for which clipping occurred are shown with a gray background.
Top ("ColorChecker 2005"): The L*a*b* and "sRGB (GMB)" data is from GretagMacbeth; the other values (xyY, Adobe, Apple, ProPhoto and sRGB) were derived from the L*a*b* data using the procedure described in Section 5.
Bottom ("BabelColor Avg."): L*a*b* and R'G'B' values were derived from the spectral average of 20 charts.

ColorChecker 2005		L*a*b* (CIE D50)			Adobe			Apple			ProPhoto			sRGB		
No.	Color name	L*	a*	b*	R'	G'	B'	R'	G'	B'	R'	G'	B'	R'	G'	B'
0	**illuminant**	**100**	**0**	**0**	**65535**	**65535**	**65535**	**65535**	**65535**	**65535**	**65535**	**65535**	**65535**	**65535**	**65535**	**65535**
1	**dark skin**	37,986	13,555	14,059	27426	21037	17932	24272	16153	13188	20795	17235	13942	29684	20794	17311
2	**light skin**	65,711	18,130	17,810	47379	37489	33025	47061	32784	27946	40907	34660	29175	51033	37831	33071
3	**blue sky**	49,927	-4,880	-21,925	25919	31234	39364	19061	26484	35753	24175	26096	34288	23285	31447	40035
4	**foliage**	43,139	-13,095	21,905	24528	27576	17662	18814	22981	12230	19249	22117	14249	23061	27664	16548
5	**blue flower**	55,112	8,844	-25,399	32927	32643	44447	28179	27684	41629	30315	28442	39678	33299	32893	45254
6	**bluish green**	70,719	-33,397	-0,199	33187	48441	44028	21635	45841	39917	32629	43161	40445	23760	48805	44209
7	**orange**	62,661	36,067	57,096	51626	31575	14313	54315	26099	7836	42868	30308	13797	57637	31797	12000
8	**purplish blue**	40,020	10,410	-45,964	19711	23542	42751	13412	18365	40089	20351	19117	37271	17444	23445	43738
9	**moderate red**	51,124	48,239	16,248	44624	21283	24831	46277	15231	20218	36263	21340	20465	50970	21055	24945
10	**purple**	30,325	22,976	-21,587	22093	15563	26707	18775	10808	22518	17495	12667	21146	24062	14904	27134
11	**yellow green**	72,532	-23,709	57,255	42816	48199	19356	37223	45581	10085	37022	43576	19080	40800	48564	16148
12	**orange yellow**	71,941	19,363	67,857	54654	41157	14181	56662	36855	4761	46640	38989	15365	59221	41533	10089
13	**blue**	28,778	14,179	-50,297	12591	16824	36877	6744	11979	33587	14563	12920	30946	9090	16275	37805
14	**green**	55,261	-38,342	31,370	25519	37925	20582	15499	34177	13894	21842	31642	17800	17200	38272	19051
15	**red**	42,101	53,378	28,190	39846	13377	15245	40882	7492	11082	30812	15251	11935	46236	12506	14638
16	**yellow**	81,733	4,039	79,819	58361	50657	13301	59657	47961	0	51240	48436	16899	61244	50998	5069
17	**magenta**	51,935	49,986	-14,574	43542	21777	37827	44678	15483	34453	36857	21856	32665	49611	21580	38695
18	**cyan**	51,038	-28,631	-28,638	15780	34706	42920	0	30411	39705	19993	28496	38002	0	35002	43613
19	**white 9.5 (.05 D)**	96,539	-0,425	1,186	62890	62936	62298	62308	62388	61541	62217	62346	61675	62954	63018	62371
20	**neutral 8 (.23 D)**	81,257	-0,638	-0,335	51294	51637	51689	48454	48985	49038	48688	48923	49018	51492	51965	52019
21	**neutral 6.5 (.44 D)**	66,766	-0,734	-0,504	41082	41470	41576	36900	37472	37587	37161	37407	37556	41301	41847	41958
22	**neutral 5 (.70 D)**	50,867	-0,153	-0,270	30850	30941	31029	26064	26190	26286	26131	26179	26268	31014	31145	31239
23	**neutral 3.5 (1.05 D)**	35,656	-0,421	-1,231	21522	21809	22201	16716	17081	17484	16932	17053	17412	21187	21613	22046
24	**black 2 (1.5 D)**	20,461	-0,079	-0,973	13424	13539	13841	9404	9535	9817	9502	9531	9770	12507	12685	13032

BabelColor Avg.		L*a*b* (CIE D50)			Adobe			Apple			ProPhoto			sRGB		
No.	Color name	L*	a*	b*	R'	G'	B'	R'	G'	B'	R'	G'	B'	R'	G'	B'
0	**illuminant**	**100**	**0**	**0**	**65535**	**65535**	**65535**	**65535**	**65535**	**65535**	**65535**	**65535**	**65535**	**65535**	**65535**	**65535**
1	**dark skin**	38,358	13,802	14,646	27427	21170	17940	24245	16287	13185	21065	17418	13958	29648	20935	17313
2	**light skin**	66,056	17,737	17,848	46858	37930	33063	46219	33312	27949	41088	34953	29396	50244	38278	33089
3	**blue sky**	50,090	-4,407	-22,512	26357	31323	39736	19634	26559	36178	24358	26172	34655	23958	31538	40419
4	**foliage**	43,204	-13,464	21,730	24611	27679	17760	18888	23087	12320	19220	22181	14334	23139	27772	16655
5	**blue flower**	55,356	8,891	-24,824	33111	32793	44393	28387	27846	41556	30507	28596	39609	33501	33047	45194
6	**bluish green**	70,700	-32,892	-0,240	34033	48634	43737	22962	46056	39544	32731	43109	40449	25382	48996	43894
7	**orange**	62,559	35,135	58,050	50616	31443	13962	52933	26017	7462	42582	30346	13468	56443	31662	11558
8	**purplish blue**	40,178	9,551	-44,289	20328	23623	42180	14223	18452	39419	20337	19254	36662	18426	23530	43150
9	**moderate red**	51,711	47,694	16,857	43878	21847	24990	45214	15889	20351	36595	21774	20603	50002	21654	25096
10	**purple**	30,375	21,131	-20,309	21538	15754	26485	18091	11025	22277	17247	12835	20734	23277	15113	26893
11	**yellow green**	72,492	-23,462	57,078	43111	48202	19192	37668	45576	9858	37047	43524	19115	41244	48567	15925
12	**orange yellow**	71,963	19,486	67,998	54237	40883	14408	56124	36556	5255	46688	38992	15334	58773	41257	10499
13	**blue**	28,653	15,600	-50,520	13494	16411	36835	8096	11556	33552	14720	12758	30949	11084	15826	37768
14	**green**	55,046	-38,088	31,617	26024	37972	20042	16294	34223	13271	21764	31474	17600	18307	38320	18395
15	**red**	42,182	54,893	28,785	38918	13259	15090	39705	7483	10945	31163	15087	11809	45152	12376	14467
16	**yellow**	82,230	4,048	79,844	58390	50936	13593	59620	48296	0	51670	48849	17164	61195	51274	5688
17	**magenta**	51,820	49,787	-13,904	42397	21730	37690	43169	15524	34301	36739	21803	32307	48247	21529	38553
18	**cyan**	50,555	-27,973	-28,139	16727	34708	42055	0	30420	38682	19852	28125	37418	0	35005	42717
19	**white 9.5 (.05 D)**	96,387	-0,404	2,238	62871	62839	61577	62323	62281	60612	62107	62194	60977	62967	62924	61645
20	**neutral 8 (.23 D)**	81,014	-0,570	0,180	51214	51454	51238	48400	48775	48492	48512	48708	48565	51453	51785	51563
21	**neutral 6.5 (.44 D)**	66,297	-0,434	-0,079	40921	41102	41054	36794	37062	36998	36885	37024	37019	41222	41477	41427
22	**neutral 5 (.70 D)**	50,830	-0,687	-0,268	30704	30992	30991	25852	26250	26240	26002	26198	26243	30782	31198	31196
23	**neutral 3.5 (1.05 D)**	35,724	-0,521	-0,468	21631	21851	21954	16842	17124	17226	16963	17093	17205	21331	21658	21772
24	**black 2 (1.5 D)**	20,706	0,025	-0,447	13618	13647	13795	9595	9628	9768	9628	9630	9743	12759	12804	12975

Table 3: R'G'B' coordinates of the ColorChecker, in **16-bit** format. Coordinates for which clipping occurred are shown with a gray background.
Top ("ColorChecker 2005"): The L*a*b* data is from GretagMacbeth; the R'G'B'values were derived from the L*a*b* data using the procedure described in Section 5.
Bottom ("BabelColor Avg."): L*a*b* and R'G'B' values were derived from the spectral average of 20 charts.

		sRGB from L*a*b* D50 (ColorChecker 2005)						sRGB (GMB) (ColorChecker 2005)						
No.	Color name	R'	G'	B'	L*a*b* (CIE D65) L*	a*	b*	R'	G'	B'	L*a*b* (CIE D65) L*	a*	b*	CIELAB ΔE*ab
1	dark skin	116	81	67	37,85	12,72	14,07	115	82	68	38,02	11,80	13,66	1,02
2	light skin	199	147	129	65,43	17,18	17,21	194	150	130	65,67	13,67	16,90	3,52
3	blue sky	91	122	156	50,15	-1,91	-21,79	98	122	157	50,63	0,37	-21,60	2,34
4	foliage	90	108	64	43,17	-15,08	22,44	87	108	67	43,00	-15,88	20,45	2,15
5	blue flower	130	128	176	55,40	11,58	-25,06	133	128	177	55,68	12,76	-25,17	1,23
6	bluish green	92	190	172	70,92	-33,22	0,29	103	189	170	70,99	-30,64	1,54	2,87
7	orange	224	124	47	62,06	33,37	56,24	214	126	44	61,14	28,10	56,13	5,35
8	purplish blue	68	91	170	40,59	16,15	-45,14	80	91	166	41,12	17,41	-41,88	3,53
9	moderate red	198	82	97	50,58	47,55	15,17	193	90	99	51,33	42,10	14,88	5,52
10	purple	94	58	106	30,51	25,11	-21,74	94	60	108	31,10	24,35	-22,10	1,02
11	yellow green	159	189	63	72,31	-27,84	57,83	157	188	64	71,90	-28,10	56,96	1,01
12	orange yellow	230	162	39	71,43	15,50	67,80	224	163	46	71,04	12,60	64,91	4,11
13	blue	35	63	147	29,46	20,74	-49,34	56	61	150	30,35	26,43	-49,67	5,77
14	green	67	149	74	55,26	-41,23	32,03	70	148	73	55,03	-40,14	32,30	1,15
15	red	180	49	57	41,53	52,67	26,92	175	54	60	41,35	49,30	24,66	4,06
16	yellow	238	198	20	81,08	-0,33	80,10	231	199	31	80,70	-3,66	77,55	4,22
17	magenta	193	84	151	51,74	51,26	-15,48	187	86	149	51,14	48,15	-15,28	3,17
18	cyan	0	136	170	52,41	-18,46	-26,64	8	133	161	51,15	-19,73	-23,37	3,72
19	white 9.5 (.05 D)	245	245	243	96,49	-0,35	0,96	243	243	242	95,82	-0,18	0,48	0,84
20	neutral 8 (.23 D)	200	202	202	81,17	-0,69	-0,24	200	200	200	80,60	0,00	0,00	0,92
21	neutral 6.5 (.44 D)	161	163	163	66,84	-0,71	-0,25	160	160	160	65,87	0,00	0,00	1,23
22	neutral 5 (.70 D)	121	121	122	50,86	0,20	-0,55	122	122	121	51,19	-0,20	0,55	1,21
23	neutral 3.5 (1.05 D)	82	84	86	35,61	-0,36	-1,44	85	85	85	36,15	0,00	0,00	1,58
24	black 2 (1.5 D)	49	49	51	20,40	0,47	-1,27	52	52	52	21,70	0,00	0,00	1,89
													avg. :	2,64

Table 4: Color difference between the sRGB coordinates derived from L*a*b* D50 values provided by GretagMacbeth, and the sRGB coordinates also provided by GretagMacbeth. The R'G'B' coordinates of the "sRGB from L*a*b* D50" data set were rounded to the nearest integer before computing the color differences. The L*a*b* values are computed for D65.

Because the cyan patch is close to the edge of the space gamut, we could expect to have some measurements which cross the border now and then; however, we have verified that the 20 individual R'G'B' values of the cyan patches used for the "BabelColor Avg." were all clipped. As an added check, for all ColorChecker patches, we compared the sRGB coordinates derived from L*a*b* D50 to the values provided by GretagMacbeth (i.e. "sRGB (GMB)"). The individual color differences and their average are shown in Table 4. Many individual differences are large, with a maximum of 5,77 for the blue patch; this is quite high, even for a blue CIELAB difference. We have further compared the differences between the other R'G'B' data sets of Table 2; the averages are shown in Table 5. For the sRGB space, the smallest average color difference (=1,30) is seen between the "sRGB from L*a*b* D50 (ColorChecker 2005)" and the "sRGB (BabelColor Avg.)" data sets.

	1st R'G'B' data set	2nd R'G'B' data set	Illum. for ΔE*ab	avg. ΔE*ab
1	sRGB from L*a*b* D50 (ColorChecker 2005)	sRGB (GMB) (ColorChecker 2005)	D65	2,64
2	sRGB from L*a*b* D50 (ColorChecker 2005)	sRGB (BabelColor Avg.)	D65	1,30
3	sRGB (GMB) (ColorChecker 2005)	sRGB (BabelColor Avg.)	D65	1,95
4	Adobe RGB from L*a*b* D50 (ColorChecker 2005)	Adobe RGB (BabelColor Avg.)	D65	1,30
5	Apple RGB from L*a*b* D50 (ColorChecker 2005)	Apple RGB (BabelColor Avg.)	D65	1,25
6	ProPhoto from L*a*b* D50 (ColorChecker 2005)	ProPhoto (BabelColor Avg.)	D50	1,03

Table 5: Average CIELAB color differences of the 24 patches of the ColorChecker for various R'G'B' data sets. The color difference is computed for the illuminant of the RGB space. See Table 4 for the details of how the result of the first row, "sRGB from L*a*b* D50" vs "sRGB (GMB)", was obtained.

As we mentioned, the "sRGB from L*a*b* D50" data of the "ColorChecker 2005" tables was determined using the Bradford chromatic adaptation transform. In comparison, the "sRGB (GMB)" data was likely determined from the spectral reflectance data, the D65 Illuminant spectral distribution and the 2-degrees Standard Observer, a method which is generally more precise. A small numeric difference is thus expected between the two methods. However, the actual average difference between these two data sets is too high (=2,64) to be explained only by chromatic transform errors only. A rough estimate of the error introduced by the Bradford transform can be obtained by comparing the average errors of the D50 and D65 spaces in Table 5, since all D65 data derived "from L*a*b* D50" was done so using the Bradford transform. When comparing the sets of rows #2, 4 and 5 to the sets of row #6, the D65 averages are 0,22 (=1,25-1,03) and 0,27 (=1,30-1,03) higher than the D50 data sets (row #6). This small difference is due essentially to the Bradford transform applied to L*a*b* D50 data. From this, we infer that the sRGB values provided by GretagMacbeth came from another data set than the one used for their L*a*b* values.

Overall, it can be seen that there is excellent agreement between the R'G'B' values of the "ColorChecker 2005" data sets derived from L*a*b* values and the "BabelColor Avg." data sets (rows #2, 4, 5, and 6). This is in fact just another way to look at what was shown in Table 1b. The best match is, as expected, between the ProPhoto data sets, since no chromatic adaptation transform was required in processing the "ColorChecker 2005" L*a*b* D50 data.

It is important to note that all these differences between data sets do not indicate which set is the best. However, the better match between the "sRGB from L*a*b* D50 (ColorChecker 2005)" and the "sRGB (BabelColor Avg.)" data sets, when compared to the large difference between the two sRGB data sets of the "ColorChecker 2005" table, tend to indicate that the "sRGB (GMB)" values are less reliable.

R'G'B' values for many other common and uncommon spaces can be found in Ref. 3.

4. RGB spaces descriptions

RGB spaces have evolved, sometimes for technological reasons (NTSC evolved to SMPTE-C), sometimes to fulfill professional requirements (ColorMatch, Adobe RGB), and sometimes because that's how the display system was built and it became a, de-facto, standard (Apple RGB).

A short description of the four spaces selected for Tables 2 and 3 follows. The position of their primaries on a CIE 1931 chromaticity diagram can be seen in Figure 1. Numerical specifications for each space are shown in Table 6.

Adobe RGB (1998)
Formerly known as SMPTE-240M for Photoshop user, this space has been renamed once the final SMPTE-240M standard committee settled for a smaller gamut[6]. Adobe RGB is very close to the original NTSC space and has a large enough gamut that encompasses the gamuts of most printing processes and displays. However, because of its gamut size, 16 bits per primary file formats should be preferred to 8 bits per primary ones, especially for editing purposes. While a relatively large number of those colors cannot be printed using the SWOP process (SWOP: Specifications for Web Offset Publications), particularly in the green portion of the gamut, newer printing processes, such as Pantone Hexachrome, take advantage of this space. Adobe RGB's white is defined with Illuminant D65.

Apple RGB
Once a very common RGB space on the desktop, it is now slowly getting phased out and replaced by sRGB, for everyday use, and by Adobe RGB (and other larger gamut spaces) for photographic and graphic design applications. Its gamut size is similar to the ones of the ColorMatch and sRGB spaces. The Apple RGB, like the ColorMatch and SGI spaces, has a non-unity display lookup-table (LUT) gamma which is compensated by the file encoding gamma (see Section 5.4 for a discussion of gamma). In older Macintosh computers, when a value of 1,8 was entered by the user in the control panel for display gamma, the LUT was filled with numbers corresponding to a gamma equal to 1,8/2,6=0,69 (or 1,45 if you define gamma using the reciprocal value =1/0,69).

ColorSync, Apple's color management technology at the operating system level, now takes care of color management for all input and output devices and will automatically convert color data from one space to another for compliant applications. Apple RGB's white is Illuminant D65.

ProPhoto
ProPhoto is a very large gamut RGB space designed by Kodak; it is getting attention from digital camera users as an archiving and working space for RAW (minimally processed, high dynamic range, and un-color-balanced) camera data.

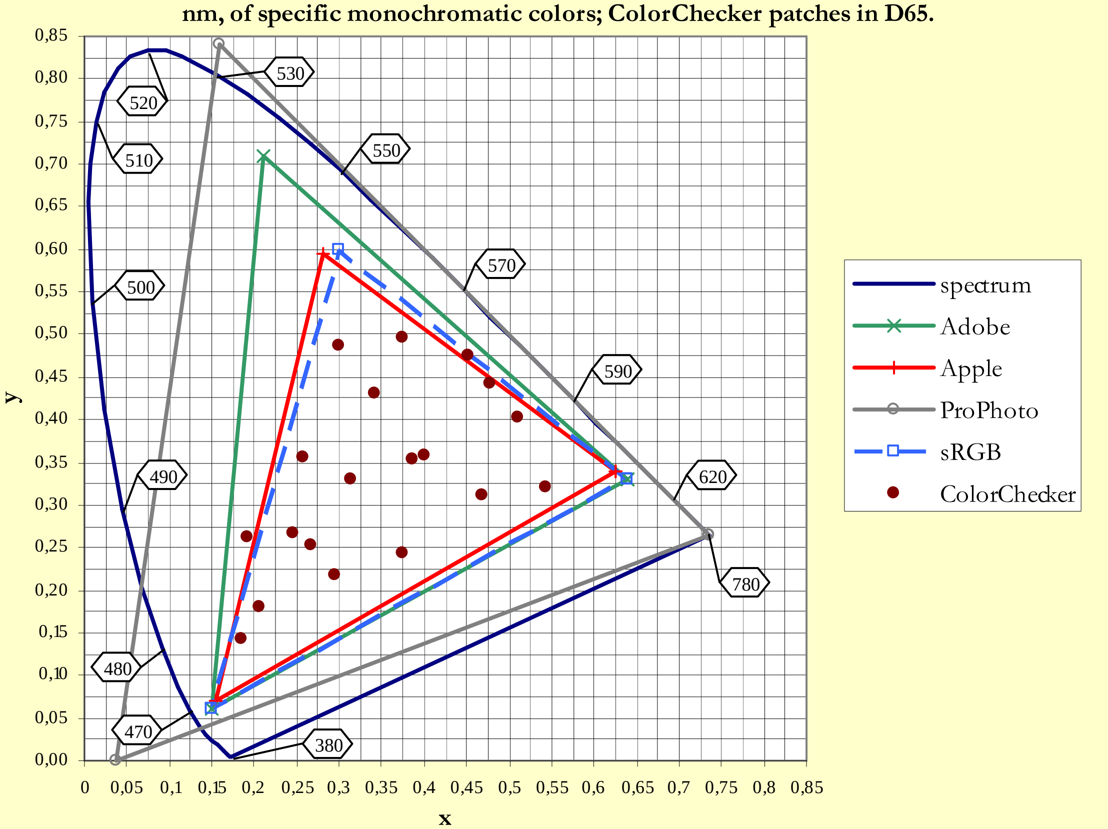
Formerly called ROMM RGB while being developed, it was renamed at the same time as its gamma was changed from 2,2 (=1/0,455) to 1,8 (=1/0,556). ProPhoto's white is Illuminant D50.

While it covers most of the visible spectrum, it also extends outside of it. As a result, about 13% of the RGB triads represent non-existent colors. Working at 16 bits per channel is a minimum with this space, and some users are concerned that even this bit depth is not enough. Others are puzzled by the decision to use a 1,8 gamma when the industry is slowly moving towards a standard 2,2 value. In any case, when used with caution for images that DO contain colors outside of the range of medium size working spaces, like Adobe RGB, it can provide improved color rendering when used in conjunction with modern wide gamut inkjet printers.

sRGB
With chromaticities identical to the ones defined in ITU-R BT.709-3, a High-Definition TV (HDTV) standard, sRGB, as defined in IEC 61966-2-1, strives to represent the evolution of the standard North-American TV and its convergence with the PC world. At the same time, its chromaticities are not very far from the ones of SMPTE-C (and SMPTE-240M), the present North-American TV standard, maintaining compatibility with the large quantity of recorded media. sRGB's white is defined with Illuminant D65.

Advertised as a general-purpose space for consumer use, sRGB is proposed for applications where embedding a color space profile, such as an ICC profile, may not be convenient for file size or compatibility purposes. By having all elements in a system sRGB compliant, no time is lost in conversions. The World Wide Web is obviously a target of choice for this space but it should not be discounted for other "scanner-to-printer" applications. An extended gamut color encoding standard has been defined for sRGB[7]; it supports multiple levels of precision while being compatible with the base standard.

Figure 1: CIE 1931 chromaticity diagram : The labels indicate the wavelengths, in nm, of specific monochromatic colors; ColorChecker patches in D65.



RGB space	Primaries / Phosphors R	G	B	White Illum.	XYZ to RGB matrix			RGB to XYZ matrix			Power Functions Exponents, i.e. gamma (γ): encoding gamma "detailed"		γ for each element of the imaging chain	
Adobe	Adobe RGB (1998)			D65	**XYZ to RGB (Adobe)**			**RGB (Adobe) to XYZ**			N.A.		"simple" encoding:	0,45 (2,20)
x :	0,6400	0,2100	0,1500	0,3127	2,0414	-0,5649	-0,3447	0,5767	0,1856	0,1882			LUT:	1
y :	0,3300	0,7100	0,0600	0,3290	-0,9693	1,8760	0,0416	0,2974	0,6273	0,0753			CRT:	0,40 (2,50)
z :	0,0300	0,0800	0,7900	0,3583	0,0134	-0,1184	1,0154	0,0270	0,0707	0,9911			overall:	1,14
Apple	Trinitron			D65	**XYZ to RGB (Apple)**			**RGB (Apple) to XYZ**			N.A.		"simple" encoding:	0,56 (1,80)
x :	0,6250	0,2800	0,1550	0,3127	2,9516	-1,2894	-0,4738	0,4497	0,3162	0,1845			LUT:	0,69 (1,45)
y :	0,3400	0,5950	0,0700	0,3290	-1,0851	1,9909	0,0372	0,2447	0,6720	0,0833			CRT:	0,40 (2,50)
z :	0,0350	0,1250	0,7750	0,3583	0,0855	-0,2695	1,0913	0,0252	0,1412	0,9225			overall:	0,96
ProPhoto	ProPhoto			D50	**XYZ to RGB (ProPhoto)**			**RGB (ProPhoto) to XYZ**			N.A.		"simple" encoding:	0,56 (1,80)
x :	0,7347	0,1596	0,0366	0,3457	1,3459	-0,2556	-0,0511	0,7977	0,1352	0,0314			LUT:	0,69 (1,45)
y :	0,2653	0,8404	0,0001	0,3585	-0,5446	1,5082	0,0205	0,2880	0,7119	0,0001			CRT:	0,4
z :	0,0000	0,0000	0,9633	0,2958	0,0000	0,0000	1,2118	0,0000	0,0000	0,8252			overall:	0,96
sRGB	HDTV (ITU-R BT.709-5)			D65	**XYZ to RGB (R709)**			**RGB (R709) to XYZ**			offset:	0,055	"simple" encoding:	**0,45** (2,20)
x :	0,6400	0,3000	0,1500	0,3127	3,2405	-1,5371	-0,4985	0,4125	0,3576	0,1804	γ :	**0,42**	LUT:	1
y :	0,3300	0,6000	0,0600	0,3290	-0,9693	1,8760	0,0416	0,2127	0,7152	0,0722	transition:	0,003	CRT:	0,40 (2,50)
z :	0,0300	0,1000	0,7900	0,3583	0,0556	-0,2040	1,0572	0,0193	0,1192	0,9503	slope:	12,92	overall:	1,14

Table 6: Colorimetric specifications of four common RGB spaces and transform matrices between linear RGB space and CIE 1931 XYZ values.

5. Data conversion process

Starting with L*a*b* data, R'G'B' (gamma corrected) triads are obtained with the following processing sequence:

a) L*a*b*$_s$ to XYZ_s
b) XYZ_s to XYZ_d (if not the same Illuminant)
c) XYZ_d to RGB_d
d) RGB_d to $R'G'B'_d$

where the source and destination spaces have an "s" and "d" subscript respectively.

Step "b)", chromatic adaptation, is required if the source and destination spaces are not based on the same illuminant. A simplified Bradford matrix transform is used for this task; it is presented in Section 5.2.

In step "c)", tristimulus XYZ values are converted to linear RGB data. This step is discussed in Section 5.3.

Step "d)" converts linear RGB values to gamma corrected R'G'B' data. This step is discussed in Section 5.4.

5.1 From L*a*b* to XYZ

The conversion from L*a*b* to XYZ is obtained with the following relations:

$$X = X_n\left[\left(\left(L^*+16\right)/116\right)+\left(a^*/500\right)\right]^3 \quad (1)$$

$$Y = Y_n\left(\left(L^*+16\right)/116\right)^3 \quad (2)$$

$$Z = Z_n\left[\left(\left(L^*+16\right)/116\right)-\left(b^*/200\right)\right]^3 \quad (3)$$

where X_n, Y_n, and Z_n are the XYZ values of the reference white. Such values are shown in Table 7 for Illuminants C, D50 and D65.

Equations (1) to (3) are valid when L* is larger than 8 and when the X/X_n, Y/Y_n, or Z/Z_n ratios are larger than 0,008856, which is the case for all patches of the ColorChecker.

	X	Y	Z
C	98,074	100	118,232
D50	96,422	100	82,521
D65	95,047	100	108,883

C --> D50		
1,0377	0,0154	-0,0583
0,0171	1,0057	-0,0189
-0,0120	0,0204	0,6906

D50 --> D65		
0,9556	-0,0230	0,0632
-0,0283	1,0099	0,0210
0,0123	-0,0205	1,3299

Table 7: XYZ coordinates of Illuminants C, D50 and D65 (2-deg. Obs.), and the Bradford Matrices between them.

$$\begin{bmatrix} Bradford \\ 3\times 3 \\ matrix \end{bmatrix} = \begin{bmatrix} 0,9870 & -0,1471 & 0,1600 \\ 0,4323 & 0,5184 & 0,0493 \\ -0,0085 & 0,0400 & 0,9685 \end{bmatrix} \bullet \begin{bmatrix} R_{dw}/R_{sw} & 0 & 0 \\ 0 & G_{dw}/G_{sw} & 0 \\ 0 & 0 & B_{dw}/B_{sw} \end{bmatrix} \bullet \begin{bmatrix} 0,8951 & 0,2664 & -0,1614 \\ -0,7502 & 1,7135 & 0,0367 \\ 0,0389 & -0,0685 & 1,0296 \end{bmatrix} \quad (6)$$

5.2 The Bradford Matrix

The colorimetric data of a sample cannot be dissociated from the characteristics of the illuminant. In the ideal case, obtaining the colorimetric coordinates of the sample under another illuminant requires reprocessing the spectral data of the sample with the spectral characteristics of the illuminant. However, this computer intensive process is not efficient and requires a large amount of data for each color. But more importantly, for most applications, like image processing, spectral data is simply not available.

To ease this task, *chromatic adaptation transforms* that transform colorimetric information using only the XYZ coordinates have been devised. All modern color appearance models competing for international acceptance[8] incorporate such a transform. One contender that has withstood critical revue is called the Bradford, or BFD for short, chromatic adaptation transform.

A simplified matrix representation of the Bradford transform was found to give excellent results during the work performed in the development of the sRGB standard[9]. In its simplified version, the only data required to generate the Bradford matrix are the XYZ coordinates of the source and destination whites. The *source white* is the illuminant used to measure the original data, and the *destination white* is the illuminant to which the data has to be translated. The Bradford conversion matrix is derived with the following relations:

$$\begin{bmatrix} R_{dw} \\ G_{dw} \\ B_{dw} \end{bmatrix} = \begin{bmatrix} 0,8951 & 0,2664 & -0,1614 \\ -0,7502 & 1,7135 & 0,0367 \\ 0,0389 & -0,0685 & 1,0296 \end{bmatrix} \bullet \begin{bmatrix} X_{dw} \\ Y_{dw} \\ Z_{dw} \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} R_{sw} \\ G_{sw} \\ B_{sw} \end{bmatrix} = \begin{bmatrix} 0,8951 & 0,2664 & -0,1614 \\ -0,7502 & 1,7135 & 0,0367 \\ 0,0389 & -0,0685 & 1,0296 \end{bmatrix} \bullet \begin{bmatrix} X_{sw} \\ Y_{sw} \\ Z_{sw} \end{bmatrix} \quad (5)$$

where $(RGB)_{dw}$ and $(XYZ)_{dw}$ are the coordinates of the destination white, and $(RGB)_{sw}$ and $(XYZ)_{sw}$ are the coordinates of the source white. In Equations (4), (5) and (6), the 3x3 matrix, with "0,8951" as its top-left element, is called the *cone response matrix*. In Equation (6), the 3x3 matrix, with "0,9870" as its top-left element, is called the *inverse cone response matrix*. These two matrices are, as their name says, the inverse of one another.

$(RGB)_{dw}$ and $(RGB)_{sw}$ are first calculated with Equations (4) and (5). XYZ coordinates can be derived from the xy coordinates of Table 6, or taken directly in Table 7. For the data presented in Tables 2 and 3, the source is always CIE Illuminant D50, with a correlated color temperature of 5000 K. Also, except for ProPhoto, all destination spaces are defined with CIE Illuminant D65, with a correlated color temperature of 6504 K, whose wavelength composition is close to that of noon daylight.

The Bradford matrix is then determined from Equation (6) using the results of the previous calculations. The Bradford matrix thus obtained between D50 and D65 is shown in Table 7.

Using the Bradford matrix, the XYZ coordinates corresponding to the illuminant of the target RGB space are:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{dest.} = \begin{bmatrix} Bradford \\ 3x3 \\ matrix \end{bmatrix} \bullet \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{source} . \qquad (7)$$

5.3 From XYZ to RGB

The XYZ to RGB matrices of Table 6 were determined according to the recommended practice RP 177-93 from the Society of Motion Picture and Television Engineers[10].

The RGB triads are obtained with the following multiplication, with Y of the illuminant normalized to 100:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} XYZ \rightarrow RGB \\ 3x3 \\ matrix \end{bmatrix} \bullet \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} . \qquad (8)$$

After this operation, the RGB coordinates of the illuminant are (100, 100, 100). All RGB triads should be rescaled at this point – divided by 100 – with the resulting RGB "white" coordinates being (1, 1, 1). Results over one or below zero are clipped at one and zero respectively.

5.4 From RGB to R'G'B' (i.e. gamma)

The eye is more sensitive to variations of luminance in low luminance levels than similar variations in high luminance levels. R'G'B' values, commonly referred to by RGB in most application software, are scaled according to this non-linear perception of the eye and more data triads are assigned to the lower luminance levels. As a result, the R'G'B' scale is close to a perceptively linear scale where doubling the values of a triad will result in a color whose brightness appears doubled.

The use of the word gamma for this compression process is an element of discord. Originally coined to explain the straight-line portion of the S-shaped (sigmoid) curve obtained when tracing, on log-log scales, the optical density of photographic film in relation to exposure, the so-called H&D curve from its inventors Hurter and Driffield, it has been since misused and overused. Some authors, for the sake of scientific rectitude, even proscribe the use of gamma in relation to displays and propose the more generic term "exponent" instead. We will nonetheless use the term gamma in this paper since it is associated with fundamental aspects of display technology and human perception, to which a generic term like "exponent" would not do justice. However, you should always verify how gamma is defined before making comparisons with other sources of information, and you should get used to the fact that any author's gamma value could be the reciprocal of another author's definition.

A very thorough presentation of modern CRT characteristics is contained in a paper by Berns, Motta and Gorzynski[11]. Easily readable presentations of gamma can be found in the book and the Internet articles of Poynton[12]. The definition of the various flavors of gamma is well presented in a tutorial that is part of the Portable Network Graphics (PNG) Specification[13] published by the World Wide Web Consortium (W3C).

A typical vision chain includes:

i- A file gamma that combines the camera gamma and the software-encoding gamma ($\gamma_{file} = \gamma_{camera} * \gamma_{encoding}$). In this document we will consider that the camera gamma and the encoding gamma are defined by the same equation, that only one of them is used at one time, and that they simply distinguish the origin of the data, either a camera or a software program.

ii- A decoding gamma, which is defined as the gamma of any transformation performed by the software reading the image file. In this document we will assume that the software does not modify the gamma once the original file is created and that the decoding gamma is equal to one.

iii- A display gamma, which combines the LUT gamma and the CRT gamma: ($\gamma_{display} = \gamma_{LUT} / \gamma_{CRT}$).

iv- The overall gamma that combines all the preceding gammas.

v- The human eye gamma.

File gamma - The effect of camera gamma is often defined in the form:

$$\left.\begin{array}{ll} V = (1+offset)L^{\gamma} - offset & \text{for } 1 \geq L \geq transition \\ V = slope \times L & \text{for } transition > L \geq 0 \end{array}\right\} \qquad (9)$$

where L is the image luminance ($0 \le L \le 1$) and V is the corresponding electrical signal (in Volt). As an example, the values prescribed (see Table 6) for the *offset*, *gamma*, *transition* and *slope* parameters for sRGB are:

$$\begin{aligned} offset &= 0{,}055 \\ \gamma &= 0{,}42 \\ transition &= 0{,}003 \\ slope &= 12{,}92 \end{aligned} \quad .$$

The function is defined by two segments: a linear segment at low light levels, below the defined transition level, which makes the transform less susceptible to noise around zero luminance, and a power segment with a 0,42 exponent. As mentioned before, the effect of that exponent is to compress the luminance signal by assigning a larger signal range to dim colors, where the eye is most sensitive, and a small signal range to bright colors.

The offset term of Equation (9) is related to what is generally identified in TVs and monitors as the *black level*, *intensity* or *brightness* control knob. The combination of (1 + offset) is related to the *picture*, *gain* or *contrast* knob. It may sound surprising to associate brightness to a DC level and contrast to a term which controls the maximum luminance level, but these terms were defined in relation to what is perceived, not the mathematical expression. In effect, the eye perceives as a brightness increase a change in the black level more than it does of a change in the gain. Note: in some displays, the brightness and contrast knobs are effectively labeled the reverse of what is "generally" found!

Equation (9) can be approximated by a simpler function of the form:

$$V = L^{\gamma} \qquad \text{for } 0 \le L \le 1 \quad , \qquad (10)$$

with a gamma optimized to fit the data of the detailed transform. Taking sRGB again as an example, a best-fit curve can be obtained with the simpler form of Equation (10) and a gamma of 0,45. The simpler form is often retained to improve computing efficiency in software applications. We used the detailed function when defined.

For software generated files, it is customary to apply a simple gamma correction of the form described in Equation (10) with an exponent value that is different between computing platforms. As shown in Table 6, this exponent is usually 0,45 (1/2,2) for Adobe(1998) and sRGB, and 0,56 (1/1,8) for Apple RGB and ProPhoto. The luminance, "L" in Equation (10), corresponds to and is linearly proportional to either one of the R, G or B channels.

The voltage "V" corresponds to the "gamma corrected" coordinates R', G', or B'. Depending on your choice of a detailed or simple gamma, R', G', and B' are determined with either one of the following equations (for simplicity, only R' is shown; G' and B' are similar; R, G, and B have to be normalized between 0 and 1 prior to this operation):

$$\left.\begin{aligned} &R' = round\left(255 \times \left((1+offset)R^{\gamma} - offset\right)\right) \\ &\qquad \text{for } 1 \ge R \ge transition\text{, and} \\ &R' = round\left(255 \times slope \times R\right) \\ &\qquad \text{for } transition > R \ge 0 \quad , \end{aligned}\right\} \qquad (11)$$

or:

$$R' = round\left(255 \times R^{\gamma}\right) \qquad \text{for } 0 \le R \le 1 \quad . \qquad (12)$$

These equations, to be used for step "d)", as defined in the processing sequence in the beginning of Section 5, are similar to Equations (9) and (10) with terms added to scale and round the values to the nearest integer between zero and 255. This scale corresponds to 8 bits per primary, a 24-bit color system. For a 16-bit system, simply replace 255 by 65 535 (=2^{16} -1).

The reverse equations are (R', G', and B' have to be normalized between 0 and 1 prior to this operation):

$$\left.\begin{aligned} &R = 255 \times \left(\frac{(R' + offset)}{(1+offset)} \right)^{1/\gamma} \\ &\qquad \text{for } 1 \ge R' \ge (transition \text{ x } slope)\text{, and} \\ &R = 255 \times R'/slope \\ &\qquad \text{for } (transition \text{ x } slope) > R' \ge 0 \quad , \end{aligned}\right\} \qquad (13)$$

or

$$R = 255 \times R'^{1/\gamma} \qquad \text{for } 0 \le R' \le 1 \quad . \qquad (14)$$

Display gamma - In Windows type PCs, the graphics card LUT is nominally a straight-line one-to-one transfer function. In Apple's Macintosh, the graphics card LUT has a transfer function as per Equation (10) with the exponent being 0,69 (1/1,45). It just so happens, and it should not be surprising, that the value of ($\gamma_{file} * \gamma_{LUT}$) is very similar for all platforms.

In many TV standards, a *reference reproducer*, which corresponds to an idealized display, is expressed in a form which is the reverse of the camera transfer function shown as Equation (9), and essentially the same as Equation (13):

$$L = \left(\frac{(V + offset)}{(1 + offset)} \right)^{1/\gamma} \quad . \qquad (15)$$

There again, a simpler, approximate, transfer function can be written:

$$L = V^{1/\gamma} \quad . \qquad (16)$$

In practice, however, the camera and display gammas are different so that the displayed contrast is higher than the original image contrast. This is done because in dim ambient conditions, a frequent condition for TV viewing, dark tones are perceived brighter than they should, due to flare from room lighting, and the black to white contrast is lower. Assuming that $\gamma_{encoding}$ and γ_{LUT} are equal to one, a normal assumption for TV work, the ratio between the camera and CRT gammas is typically fixed to 1,25 for dim viewing conditions[14].

In a properly set monitor for color related work, it is recommended to adjust the black level, or offset, near zero, i.e. barely perceptible from a no-signal state. Also, it is recommended to adjust the video gain – the contrast – to maximum value. This is the method used in the Adobe Gamma "Control Panel" tool provided with many Adobe products, and a paper by J. R. Jiménez & al.[15] confirms that this procedure maximizes the color gamut.

Berns & al.[16] present data from properly set monitors that are best fitted, using Equation (15), with a gamma of 0,406 (1/2,46) and an offset of zero. In this case Equation (15) corresponds exactly to Equation (16). A rounded value of 0,4 (1/2,5) is used for CRT gamma in Table 6.

Overall gamma - The overall system gamma is:

$$\gamma_{overall} = \frac{\gamma_{file} \times \gamma_{LUT}}{\gamma_{CRT}} \quad . \qquad (17)$$

It can be seen in Table 6 that the overall gamma varies between 0,96 and 1,14, somewhat lower values than the 1,25 ratio usually expected for TV viewing. This result is consistent with the brighter displays typically used for computer work and the correspondingly higher, in fact more normally, perceived contrast. At some point however, veiling glare could lower the contrast again. This explains why professional systems have glare protecting hoods around monitors, as well as neutral gray bezels – and sometimes an entirely gray workplace – to prevent unwanted color contamination.

Human eye gamma - The human eye has a response similar to the one assigned for cameras. In the L*a*b* color space, one of the "more" uniform color spaces standardized by the CIE, the perceived luminance L*, called lightness, is essentially the same as Equation (9) but with a 0,33 (1/3) exponent.

The L*a*b* is derived from the XYZ data with the following transform (from Ref. 14):

$$\left.\begin{aligned} L^* &= 116\left(Y/Y_n\right)^{1/3} - 16 && \text{(for } Y/Y_n > 0{,}008856\text{)} \\ L^* &= 903{,}3\left(Y/Y_n\right) && \text{(for } Y/Y_n \le 0{,}008856\text{)} \\ a^* &= 500\left(\left(X/X_n\right)^{1/3} - \left(Y/Y_n\right)^{1/3}\right) \\ b^* &= 200\left(\left(Y/Y_n\right)^{1/3} - \left(Z/Z_n\right)^{1/3}\right) \end{aligned}\right\} \quad (18)$$

where (X_n, Y_n, Z_n) are the illuminant's coordinates. The camera signals, or encoded file data if the image is generated directly in software, are thus compressed in an efficient way with more signal range associated with the lower brightness colors where the eye has more discrimination. To be viewed, the image goes through the graphics LUT and the CRT electronics, a path that effectively decompresses the recorded signal so that the eye can perceive it as if he saw the original scene, with more or less correction further applied to account for viewing conditions.

6. Conversion process accuracy

Color differences can be expressed mathematically for any space but they make practical sense only for the more uniform spaces where the resulting numbers can be better associated to what the eye perceives.

For the L*a*b* space the CIELAB color difference equation is, again from Ref. 14:

$$\Delta E^*_{ab} = \left[\left(\Delta a^*\right)^2 + \left(\Delta b^*\right)^2 + \left(k\Delta L^*\right)^2\right]^{1/2} \quad , \qquad (19)$$

where k=1 for samples compared in close proximity (k=0,5 or less for samples compared further away from each other, where the eye is less sensitive to lightness differences). A ΔE^*_{ab}=1 corresponds to colors which are barely differentiable by 50% of a group of observers; the other 50% would see no difference. Even though Equation (19) is a workhouse of the color industry, its statistical threshold is a cause of concern, and of possible litigation, in many industrial applications where expert observers' judgments are confronted. For this reason, better color difference equations are being sought, such as CIEDE2000 (see Ref. 5), which is itself being closely evaluated[17]. We will nonetheless evaluate the conversion

Processing step	Average ΔE^*_{ab} error	Standard deviation	Notes
Bradford matrix	1,4	0,9	Measured for a D65 to D50 conversion. From Ref. 18.
XYZ to RGB (matrix)	≈ 0	≈ 0	Negligible error when constants with at least 4 significant decimals are used.
XYZ to RGB (clipping)	variable	variable	See text.
RGB to R'G'B' (simple vs. detailed gamma)	1,3	0,92	When a simple gamma expression is used instead of a detailed one (when available). Measured for sRGB.
RGB to R'G'B' (rounding error)	0,23	0,11	Typical values. Values are slightly higher for larger spaces (Ex.: 0,28 average for Adobe (1998)).

Table 8: Typical errors associated to a XYZ to R'G'B' conversion. Errors due to clipping are not considered.

accuracy using CIELAB since there are few studies based on the newer color difference formulas.

When converting from one space to another, beside the inherent errors coming from the accuracy of the original data, the conversion process can introduce additional errors from the number of decimal places used in the conversion matrices constants, from the approximate form of the Bradford matrix, from the clipping required to limit RGB values between zero and one, from the use of a simple gamma instead of a detailed gamma, and from the rounding of the R'G'B' values. Table 8 shows typical errors associated with each operation.

A detailed evaluation of the Bradford matrix accuracy was performed on more than 1 000 colors from the Pantone color data set covering a very large gamut[18]. A first set of color coordinates was determined from spectral data and the D65 illuminant with a method similar to the one described in ASTM E308-99[19]. A second set of coordinates was obtained by converting XYZ data, obtained from spectral data and with Illuminant D50, to Illuminant D65 using the simplified Bradford matrix. The average ΔE^*_{ab} error between the two sets was 1,4 with a standard deviation of 0,9. This difference is essentially a Color Inconstancy effect, an effect related to metamerism, since the Bradford matrix assumes that the same color is perceived for all illuminants while the detailed spectral calculation determines the actual perceived color. We performed the same evaluation for the ColorChecker patches, converting between the D50 and D65 illuminants; the average ΔE^*_{ab} error for all patches is 1,0, with the average being 1,35 when considering only the chromatic patches, and 0,12 for the six neutral patches.

The error associated with the Bradford matrix presented above does not include any effect resulting from the precision of the matrix terms. If matrix elements with at least four significant decimals are used, then virtually no error is induced by the mathematics of the conversion. This is also true for the XYZ to RGB matrix.

Clipping error values are not shown in this table since they are very dependent of the specific target space and the gamut of the original data. Clipping will most often be noticed for images which exhibit single-color large-area zones, an annoying situation if that color is associated with a "brand" product. This is where the use of "spot" colors – additional printing plates for dedicated colored inks other than CMY – is justified in many graphic design applications. For the ColorChecker chart, clipping occurs for the cyan patch in many smaller RGB spaces; other patches may also be clipped in various spaces. These cases are identified in Tables 2 and 3.

Using a simple gamma expression when a detailed one is available adds a ΔE^*_{ab} of 1,3 on average with a standard deviation of 0,92, about the same as for the Bradford matrix.

Rounding the R'G'B' values to the nearest integers introduces an inevitable error of 0,23, on average, which is not noticeable. However, multiple conversions between different RGB spaces could degrade the color fidelity to a point where it could be noticed.

Processing steps	**Average ΔE^*_{ab} error**
L*a*b* to XYZ	0
Bradford matrix: XYZ_{D50} to XYZ_{D65}	1,4
XYZ to RGB: matrix math.	0
XYZ to RGB: clipping	Not included
RGB to R'G'B': detailed gamma	0
RGB to R'G'B': R'G'B' rounding	0,23
Combined RSS error	**1,42**

Table 9: The error budget associated with the conversion of L*a*b* D50 values to sRGB R'G'B' coordinates, which are based on D65. The RGB to R'G'B' conversion is performed with a detailed gamma expression.

The errors of Table 8 should not be added since they are statistical in nature. The combined effect of multiple processes can be evaluated by calculating the Root-Sum-Squared (RSS) value:

$$RSS\_error = \left[(error\#1)^2 + (error\#2)^2 + \cdots + (error\#n)^2\right]^{1/2} . \quad (20)$$

As an example, Table 9 shows the error budget associated with the conversion from L*a*b* D50 to sRGB. An average ΔE^*_{ab} error of 1,42 can be expected. However, as mentioned a few paragraphs ago, we know that the average Bradford matrix error will be less for the ColorChecker patches, which is indirectly confirmed by comparing, in Table 5, the D50 data sets (row #6) to the D65 data sets (rows #2, 4 and 5).

To place these errors in perspective, we should take into consideration the conditions in which these patches will be seen. One of these conditions is the observation time.

According to a review article by Has & al.[20], an inexperienced user will take approximately 5 seconds to notice a ΔE^*_{ab} difference of 15 from an original. The time goes up to 10 seconds for a ΔE^*_{ab} of 10, and 15 seconds for a ΔE^*_{ab} of 5. Another study[21] has shown that errors of less than 2,5 ΔE^*_{ab} are not visible on real world images shown on a CRT. In essence, the threshold value of ΔE^*_{ab} = 1 can only be achieved only by prolonged comparative viewing in a controlled environment.

On the hardware side, it has been shown[22] that CRTs require a warm-up time varying between 15 minutes and three hours, depending on models, before achieving a long term stability of 0,15 ΔE^*_{ab} on average. On a given CRT subjected to a large luminance variation, an initial ΔE^*_{ab} of 1,0 was seen to exponentially decrease to about 0,1 ΔE^*_{ab} in 60 seconds. Similar information for LCD displays is not readily available, but the fluorescent back-lamps used in almost all of these devices are susceptible to warm-up effects. As for printed material, errors between 2 and 4 ΔE^*_{ab} are mentioned by Has & al. for the offset and rotogravure process.

7. Discussion

We have seen that the L*a*b* D50 reference data provided by GretagMacbeth ("ColorChecker 2005") is in very good agreement with the average compiled from user measurements ("BabelColor Avg."), and to data derived from a spectral reference file which is given with GretagMacbeth's ProfileMaker software package ("ProfileMaker 2004"). These three data sets are, on average, very similar, and could be used interchangeably. However, since the L*a*b* D50 values provided by GretagMacbeth are included with the product and can be found readily, they are likely to be used more often. For batch to batch tolerances, and to see the typical spectral variations of specific patches, you should consult the data available in Ref. 3.

For R'G'B' coordinates of D50 spaces, such as ProPhoto in this document and many other spaces in Ref. 3, we leave it to the reader to select either the "ColorChecker 2005" or the "BabelColor Avg." data set, as they see fit. There are essentially equivalent.

For the D65 spaces, we see a small advantage of using the R'G'B' coordinates determined from the "BabelColor Avg." data set, because they are not subject to Bradford transform errors, like the ones derived from L*a*b* D50 in the "ColorChecker 2005" tables. For those who may have a preference for the R'G'B' coordinates of the "ColorChecker 2005" tables, we do not recommend the coordinates provided by GretagMacbeth, labeled "sRGB (GMB)" in Table 2. We suggest using, instead, the values derived from the GretagMacbeth L*a*b* D50 data.

The "ColorChecker 1976" data set, the only official data available until now, was shown to be less representative than the more recent data sets we evaluated. The 1976 data set, and all the data derived from it, should not be used anymore.

Of course, if you can measure your own chart and if you only use images of this same chart, your measured values should be more precise than the ones provided herein. However, when dealing with images of an unknown chart, the values from this document (and Ref. 3) will be more accurate than any single chart data.

The ColorChecker is finding much use as a reference in the RAW files workflow of digital photography. It is important to note that, in order to properly use the reference numbers, the chart should be well lit. In particular, it should not be in a shadow, or in a position where its colors are influenced by the color of one scene element, such as foliage in a forest, unless this is done for a specific reason.

You should also not assume that the ColorChecker covers the entire lightness range since its "white" and "black" patches, number 19 and 24 in Tables 1, 2, and 3, are not the whitest (and most neutral) white and the blackest black one can find. If you adjust your image white point to the ColorChecker white, you will likely have many other white objects saturated. Similarly, you may clip many shadows if you set your black point on the ColorChecker black patch. Whiter and blacker targets are respectively required for these tasks.

When comparing displayed or printed patches with the original set, you may find that there are differences for some or all of the reproduced colors. These differences are most likely due to non-calibrated displays, non-calibrated printers, or wrong printer drivers. Even when using what may seem as the "proper" International Color Consortium (ICC) profile, such as a profile provided by a printer manufacturer for a specific paper, a print may not look perfect. This, in turn, may simply be attributed to a profile which is not representative of all production units or ink batches, a situation which highlights the limits of the technology. Although more expensive in terms of process time and hardware requirements, user generated ICC profiles should be used for best results instead of the generic ones supplied by the devices manufacturers. Software and procedures to perform this calibration based on the ColorChecker chart do exist but more accurate results are obtained by using a larger number of patches, sometimes up in the thousands for high-end applications.

Now in its 30th year of existence, the ColorChecker has gracefully survived the transition from silver-based to digital-based photography. It is in fact, more than ever, an indispensable tool for the serious amateur and professional photographer.

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About the author

Danny Pascale founded *The BabelColor Company* in 2003 to develop and sell software dedicated to the measurement and analysis of color.

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