RGB coordinates of the Macbeth ColorChecker

Danny Pascale
The BabelColor Company
dpascale@BabelColor.com
www.BabelColor.com
© 2000-2006 Danny Pascale

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 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 simpler 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. 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.

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. 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)

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>
<thead>
<tr>
<th>No.</th>
<th>Color name</th>
<th>ColorChecker 2005</th>
<th>ColorChecker 1976</th>
<th>ΔL*</th>
<th>Δa*</th>
<th>Δb*</th>
<th>CIELAB DE2000</th>
<th>ΔE</th>
<th>ΔE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>dark skin</td>
<td>37.99, 13.56, 14.06</td>
<td>38.14, 13.81, 14.75</td>
<td>0.75</td>
<td>0.45</td>
<td>0.59</td>
<td>0.78</td>
<td>1</td>
<td>ΔE ≤ 1</td>
</tr>
<tr>
<td>2</td>
<td>light skin</td>
<td>65.71, 18.13, 17.81</td>
<td>66.63, 15.38, 17.30</td>
<td>2.95</td>
<td>2.01</td>
<td>1.91</td>
<td>2.98</td>
<td>2</td>
<td>1 &lt; ΔE ≤ 2</td>
</tr>
<tr>
<td>3</td>
<td>blue sky</td>
<td>49.93, -4.88, -21.93</td>
<td>50.73, -3.15, -22.43</td>
<td>1.98</td>
<td>1.75</td>
<td>1.91</td>
<td>1.98</td>
<td>3</td>
<td>2 &lt; ΔE ≤ 4</td>
</tr>
<tr>
<td>4</td>
<td>foliage</td>
<td>43.14, -13.10, 21.91</td>
<td>43.36, -14.99, 21.85</td>
<td>1.91</td>
<td>1.32</td>
<td>1.91</td>
<td>1.91</td>
<td>4</td>
<td>4 &lt; ΔE ≤ 5</td>
</tr>
<tr>
<td>5</td>
<td>blue flower</td>
<td>55.11, 8.84, -25.40</td>
<td>56.01, 9.63, -25.74</td>
<td>1.24</td>
<td>0.98</td>
<td>1.24</td>
<td>1.24</td>
<td>5</td>
<td>4 &lt; ΔE ≤ 5</td>
</tr>
<tr>
<td>6</td>
<td>bluish green</td>
<td>70.72, -33.40, -0.199</td>
<td>71.50, -31.93, 0.831</td>
<td>1.95</td>
<td>1.09</td>
<td>1.95</td>
<td>1.95</td>
<td>6</td>
<td>4 &lt; ΔE ≤ 5</td>
</tr>
<tr>
<td>7</td>
<td>orange</td>
<td>62.66, 36.07, 57.10</td>
<td>62.28, 31.88, 58.56</td>
<td>4.45</td>
<td>2.72</td>
<td>4.45</td>
<td>4.45</td>
<td>7</td>
<td>4 &lt; ΔE ≤ 5</td>
</tr>
<tr>
<td>8</td>
<td>purplish blue</td>
<td>40.02, 10.41, -45.96</td>
<td>40.44, 11.42, -44.07</td>
<td>2.19</td>
<td>1.61</td>
<td>2.19</td>
<td>2.19</td>
<td>8</td>
<td>4 &lt; ΔE ≤ 5</td>
</tr>
<tr>
<td>9</td>
<td>moderate red</td>
<td>51.12, 48.24, 16.25</td>
<td>51.94, 45.25, 15.56</td>
<td>3.17</td>
<td>2.62</td>
<td>3.17</td>
<td>3.17</td>
<td>9</td>
<td>4 &lt; ΔE ≤ 5</td>
</tr>
<tr>
<td>10</td>
<td>purple</td>
<td>30.33, 22.98, -21.59</td>
<td>30.50, 23.99, -23.63</td>
<td>2.30</td>
<td>1.06</td>
<td>2.30</td>
<td>2.30</td>
<td>10</td>
<td>4 &lt; ΔE ≤ 5</td>
</tr>
<tr>
<td>11</td>
<td>yellow green</td>
<td>72.53, -23.71, 57.26</td>
<td>72.83, -23.76, 58.64</td>
<td>1.41</td>
<td>0.48</td>
<td>1.41</td>
<td>1.41</td>
<td>11</td>
<td>4 &lt; ΔE ≤ 5</td>
</tr>
<tr>
<td>12</td>
<td>orange yellow</td>
<td>71.94, 19.36, 67.88</td>
<td>72.18, 17.40, 66.70</td>
<td>2.29</td>
<td>1.08</td>
<td>2.29</td>
<td>2.29</td>
<td>12</td>
<td>4 &lt; ΔE ≤ 5</td>
</tr>
<tr>
<td>14</td>
<td>green</td>
<td>55.26, -38.34, 31.37</td>
<td>55.66, -38.77, 33.09</td>
<td>1.82</td>
<td>0.77</td>
<td>1.82</td>
<td>1.82</td>
<td>14</td>
<td>4 &lt; ΔE ≤ 5</td>
</tr>
<tr>
<td>15</td>
<td>red</td>
<td>42.10, 53.38, 28.19</td>
<td>41.71, 53.43, 26.98</td>
<td>1.27</td>
<td>0.73</td>
<td>1.27</td>
<td>1.27</td>
<td>15</td>
<td>4 &lt; ΔE ≤ 5</td>
</tr>
<tr>
<td>16</td>
<td>yellow</td>
<td>81.73, -4.04, -79.82</td>
<td>81.95, 1.65, -78.47</td>
<td>2.75</td>
<td>1.40</td>
<td>2.75</td>
<td>2.75</td>
<td>16</td>
<td>4 &lt; ΔE ≤ 5</td>
</tr>
<tr>
<td>17</td>
<td>magenta</td>
<td>51.94, 49.99, -14.57</td>
<td>51.57, 48.99, -15.57</td>
<td>1.46</td>
<td>0.72</td>
<td>1.46</td>
<td>1.46</td>
<td>17</td>
<td>4 &lt; ΔE ≤ 5</td>
</tr>
<tr>
<td>18</td>
<td>cyan</td>
<td>51.04, -28.63, -28.64</td>
<td>51.07, -28.01, -27.36</td>
<td>1.42</td>
<td>0.54</td>
<td>1.42</td>
<td>1.42</td>
<td>18</td>
<td>4 &lt; ΔE ≤ 5</td>
</tr>
<tr>
<td>19</td>
<td>white 9.5 (0.5 D)</td>
<td>96.54, -0.425, 1.186</td>
<td>96.09, -0.062, 0.067</td>
<td>1.29</td>
<td>1.25</td>
<td>1.29</td>
<td>1.29</td>
<td>19</td>
<td>4 &lt; ΔE ≤ 5</td>
</tr>
<tr>
<td>20</td>
<td>neutral 8 (2.3 D)</td>
<td>81.26, -0.638, -0.335</td>
<td>81.35, -0.054, 0.058</td>
<td>0.71</td>
<td>0.94</td>
<td>0.71</td>
<td>0.71</td>
<td>20</td>
<td>4 &lt; ΔE ≤ 5</td>
</tr>
<tr>
<td>21</td>
<td>neutral 6.5 (4.4 D)</td>
<td>66.77, -0.734, -0.504</td>
<td>66.67, -0.046, 0.049</td>
<td>0.89</td>
<td>1.14</td>
<td>0.89</td>
<td>0.89</td>
<td>21</td>
<td>4 &lt; ΔE ≤ 5</td>
</tr>
<tr>
<td>22</td>
<td>neutral 5 (7.0 D)</td>
<td>50.87, -0.153, -0.270</td>
<td>51.58, -0.037, 0.040</td>
<td>0.78</td>
<td>0.79</td>
<td>0.78</td>
<td>0.78</td>
<td>22</td>
<td>4 &lt; ΔE ≤ 5</td>
</tr>
<tr>
<td>23</td>
<td>neutral 3.5 (1.05 D)</td>
<td>35.66, -0.421, -1.231</td>
<td>35.99, -0.029, 0.031</td>
<td>1.36</td>
<td>1.38</td>
<td>1.36</td>
<td>1.36</td>
<td>23</td>
<td>4 &lt; ΔE ≤ 5</td>
</tr>
<tr>
<td>24</td>
<td>black 2 (1.5 D)</td>
<td>20.46, -0.079, -0.973</td>
<td>20.56, -0.020, 0.022</td>
<td>1.00</td>
<td>0.98</td>
<td>1.00</td>
<td>1.00</td>
<td>24</td>
<td>4 &lt; ΔE ≤ 5</td>
</tr>
<tr>
<td></td>
<td>avg.</td>
<td></td>
<td></td>
<td>2.00</td>
<td>1.23</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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: 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 III-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'Eclairage (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.

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.
### Table 2: R'G'B' coordinates of the ColorChecker, in 8-bit format.

Coordinates for which clipping occurred are shown with a gray background.

<table>
<thead>
<tr>
<th>ColorChecker</th>
<th>xyY (CIE D50)</th>
<th>L’a<em>b</em> (CIE D50)</th>
<th>Adobe</th>
<th>Apple</th>
<th>ProPhoto</th>
<th>sRGB</th>
<th>sRGB (GMB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>Color name</td>
<td>x</td>
<td>y</td>
<td>Y</td>
<td>L* a* b*</td>
<td>R' G' B'</td>
<td>R' G' B'</td>
</tr>
<tr>
<td>0</td>
<td>illuminant</td>
<td>0.3457</td>
<td>0.3585</td>
<td>100</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>dark skin</td>
<td>0.3436</td>
<td>0.3787</td>
<td>10.29</td>
<td>38.56</td>
<td>11.30</td>
<td>14.65</td>
</tr>
<tr>
<td>2</td>
<td>light skin</td>
<td>0.4187</td>
<td>0.3749</td>
<td>35.40</td>
<td>66.26</td>
<td>17.31</td>
<td>17.85</td>
</tr>
<tr>
<td>3</td>
<td>blue sky</td>
<td>0.2757</td>
<td>0.2996</td>
<td>18.49</td>
<td>50.09</td>
<td>-4.41</td>
<td>-22.51</td>
</tr>
<tr>
<td>4</td>
<td>foliage</td>
<td>0.3688</td>
<td>0.4501</td>
<td>12.57</td>
<td>43.20</td>
<td>-53.38</td>
<td>28.19</td>
</tr>
<tr>
<td>5</td>
<td>blue flower</td>
<td>0.3016</td>
<td>0.2871</td>
<td>23.28</td>
<td>55.36</td>
<td>-8.89</td>
<td>-24.82</td>
</tr>
<tr>
<td>6</td>
<td>bluish green</td>
<td>0.3253</td>
<td>0.3032</td>
<td>19.30</td>
<td>51.04</td>
<td>-28.63</td>
<td>-28.64</td>
</tr>
<tr>
<td>7</td>
<td>9.5 (0.65 D)</td>
<td>0.3469</td>
<td>0.3608</td>
<td>91.31</td>
<td>96.54</td>
<td>-0.43</td>
<td>1.19</td>
</tr>
<tr>
<td>8</td>
<td>neutral 8.3 (D)</td>
<td>0.3440</td>
<td>0.3584</td>
<td>58.94</td>
<td>81.26</td>
<td>-0.64</td>
<td>-0.34</td>
</tr>
<tr>
<td>9</td>
<td>6.5 (1.44 D)</td>
<td>0.3432</td>
<td>0.3581</td>
<td>36.32</td>
<td>66.77</td>
<td>-0.73</td>
<td>-0.50</td>
</tr>
<tr>
<td>10</td>
<td>neutral 7.0 (D)</td>
<td>0.3446</td>
<td>0.3579</td>
<td>19.15</td>
<td>50.87</td>
<td>-0.15</td>
<td>-0.27</td>
</tr>
<tr>
<td>11</td>
<td>neutral 3.5 (1.05 D)</td>
<td>0.3401</td>
<td>0.3548</td>
<td>8.83</td>
<td>35.66</td>
<td>-0.42</td>
<td>-1.23</td>
</tr>
<tr>
<td>12</td>
<td>black 2 (1.5 D)</td>
<td>0.3406</td>
<td>0.3537</td>
<td>3.11</td>
<td>20.46</td>
<td>-0.08</td>
<td>-0.97</td>
</tr>
</tbody>
</table>
### Table 3: R'G'B' coordinates of the ColorChecker, in 24-bit format. Coordinates for which clipping occurred are shown with a gray background.

#### BabelColor Avg.

<table>
<thead>
<tr>
<th>No.</th>
<th>Color name</th>
<th>L<em>a</em>b* (CIE D50)</th>
<th>Adobe</th>
<th>Apple</th>
<th>ProPhoto</th>
<th>sRGB</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>illuminant</td>
<td>100 0 0</td>
<td>65535</td>
<td>65535</td>
<td>65535</td>
<td>65535</td>
</tr>
<tr>
<td>1</td>
<td>dark skin</td>
<td>37,986 13,555 14,059</td>
<td>27426 21037 17932</td>
<td>24272 16153 13188</td>
<td>20795 17235 13942</td>
<td>29684 20794 17311</td>
</tr>
<tr>
<td>2</td>
<td>light skin</td>
<td>65,711 18,130 17,810</td>
<td>47379 37489 33025</td>
<td>47061 32784 27946</td>
<td>40907 34660 29175</td>
<td>51033 37831 33071</td>
</tr>
<tr>
<td>3</td>
<td>blue sky</td>
<td>59,924 -4,880 -21,925</td>
<td>25919 31234 39364</td>
<td>19061 26484 55735</td>
<td>24175 26096 34288</td>
<td>23385 31447 40035</td>
</tr>
<tr>
<td>4</td>
<td>foliage</td>
<td>43,139 -13,095 21,905</td>
<td>24528 25756 17662</td>
<td>18814 22981 12230</td>
<td>19249 22117 14249</td>
<td>23651 27664 16548</td>
</tr>
<tr>
<td>5</td>
<td>blue flower</td>
<td>55,112 8,844 -25,399</td>
<td>32927 32643 44447</td>
<td>28179 27648 16429</td>
<td>30315 28442 39678</td>
<td>32939 32893 45254</td>
</tr>
<tr>
<td>6</td>
<td>bluish green</td>
<td>70,719 -33,397 -19,099</td>
<td>33187 48441 44028</td>
<td>21635 45841 39917</td>
<td>32629 43161 40445</td>
<td>23760 48805 44209</td>
</tr>
<tr>
<td>7</td>
<td>orange</td>
<td>62,661 36,067 57,096</td>
<td>51626 53175 14113</td>
<td>54315 52099 7386</td>
<td>42978 51308 12175</td>
<td>56317 51308 12000</td>
</tr>
<tr>
<td>8</td>
<td>purplish blue</td>
<td>40,020 10,410 -45,964</td>
<td>19711 23542 42751</td>
<td>13412 18365 40089</td>
<td>20351 19117 37271</td>
<td>17444 23445 43738</td>
</tr>
<tr>
<td>9</td>
<td>moderate red</td>
<td>51,124 48,239 16,248</td>
<td>24624 21263 24831</td>
<td>46277 52131 20128</td>
<td>36263 21340 26405</td>
<td>50970 21055 24945</td>
</tr>
<tr>
<td>10</td>
<td>purple</td>
<td>30,325 22,976 -21,587</td>
<td>22093 15563 26707</td>
<td>18775 10808 22518</td>
<td>1749 21667 21146</td>
<td>24064 19404 27314</td>
</tr>
<tr>
<td>11</td>
<td>yellow green</td>
<td>72,532 -23,709 57,255</td>
<td>42816 48199 19356</td>
<td>37223 54581 10805</td>
<td>37022 43576 19808</td>
<td>40800 48562 16148</td>
</tr>
<tr>
<td>12</td>
<td>orange yellow</td>
<td>71,941 19,363 67,857</td>
<td>54654 41157 14181</td>
<td>56662 36855 4761</td>
<td>46460 38938 15065</td>
<td>99221 41533 10089</td>
</tr>
<tr>
<td>13</td>
<td>blue</td>
<td>28,778 14,179 -50,297</td>
<td>12591 16824 36877</td>
<td>6744 11979 33587</td>
<td>14563 12920 30946</td>
<td>90900 16275 37805</td>
</tr>
<tr>
<td>14</td>
<td>green</td>
<td>55,261 -53,342 31,370</td>
<td>25519 35971 20525</td>
<td>40882 7492 11082</td>
<td>30812 15251 11935</td>
<td>46236 12506 14636</td>
</tr>
<tr>
<td>15</td>
<td>red</td>
<td>42,101 53,378 28,190</td>
<td>39886 13377 15427</td>
<td>44678 15483 34543</td>
<td>36857 21856 32665</td>
<td>49611 21580 38695</td>
</tr>
<tr>
<td>16</td>
<td>yellow</td>
<td>81,733 4,039 79,819</td>
<td>58361 30573 13301</td>
<td>51035 49869 10790</td>
<td>51240 45562 2181</td>
<td>61244 50998 50669</td>
</tr>
<tr>
<td>17</td>
<td>magenta</td>
<td>51,935 49,986 -14,574</td>
<td>43542 21777 37827</td>
<td>44678 15483 34543</td>
<td>36857 21856 32665</td>
<td>49611 21580 38695</td>
</tr>
<tr>
<td>18</td>
<td>cyan</td>
<td>51,090 -28,631 26,638</td>
<td>15780 34706 49209</td>
<td>0 30411 39705</td>
<td>19993 28496 38002</td>
<td>0 35002 43613</td>
</tr>
<tr>
<td>19</td>
<td>white 9.5 (.05 D)</td>
<td>96,539 4,025 14,186</td>
<td>62980 29363 62299</td>
<td>62308 62388 61541</td>
<td>62217 63463 16675</td>
<td>62954 63018 62371</td>
</tr>
<tr>
<td>20</td>
<td>neutral 8 (.23 D)</td>
<td>81,257 4,068 14,305</td>
<td>51294 51637 51689</td>
<td>48454 48985 49038</td>
<td>48688 49203 19801</td>
<td>51492 51965 52019</td>
</tr>
<tr>
<td>21</td>
<td>neutral 6.5 (.44 D)</td>
<td>66,766 -4,734 14,468</td>
<td>41080 41470 41576</td>
<td>36690 37472 37587</td>
<td>37161 37407 37556</td>
<td>41301 41847 41958</td>
</tr>
<tr>
<td>22</td>
<td>neutral 5 (.70 D)</td>
<td>50,867 4,073 14,756</td>
<td>13050 19063 19245</td>
<td>26064 26190 26286</td>
<td>2631 26179 26268</td>
<td>31014 31145 31239</td>
</tr>
<tr>
<td>23</td>
<td>neutral 3.5 (1.05 D)</td>
<td>35,656 -4,021 1,231</td>
<td>21522 21809 22201</td>
<td>16716 17081 17484</td>
<td>16932 17053 17412</td>
<td>21187 21613 22046</td>
</tr>
<tr>
<td>24</td>
<td>black 2 (1.5 D)</td>
<td>20,461 -4,079 1,231</td>
<td>13424 13539 13841</td>
<td>9404 9535 9817</td>
<td>9502 9531 9770</td>
<td>12507 12685 13032</td>
</tr>
</tbody>
</table>
Table 5: Average CIELAB color differences of the 24 patches

<table>
<thead>
<tr>
<th>No.</th>
<th>Color name</th>
<th>R*</th>
<th>G*</th>
<th>B*</th>
<th>L<em>a</em></th>
<th>a*</th>
<th>b*</th>
<th>ΔE*&lt;sub&gt;ab&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>dark skin</td>
<td>116</td>
<td>81</td>
<td>67</td>
<td>37.85</td>
<td>12.72</td>
<td>14.07</td>
<td>1.02</td>
</tr>
<tr>
<td>2</td>
<td>light skin</td>
<td>199</td>
<td>147</td>
<td>129</td>
<td>65.43</td>
<td>17.18</td>
<td>17.21</td>
<td>3.52</td>
</tr>
<tr>
<td>3</td>
<td>blue sky</td>
<td>91</td>
<td>122</td>
<td>156</td>
<td>50.15</td>
<td>-1.91</td>
<td>-21.79</td>
<td>2.34</td>
</tr>
<tr>
<td>4</td>
<td>foliage</td>
<td>90</td>
<td>108</td>
<td>64</td>
<td>43.17</td>
<td>-15.08</td>
<td>22.44</td>
<td>2.15</td>
</tr>
<tr>
<td>5</td>
<td>blue flower</td>
<td>130</td>
<td>128</td>
<td>176</td>
<td>55.40</td>
<td>11.58</td>
<td>-25.06</td>
<td>1.23</td>
</tr>
<tr>
<td>6</td>
<td>bluish green</td>
<td>92</td>
<td>190</td>
<td>172</td>
<td>70.92</td>
<td>-33.22</td>
<td>0.29</td>
<td>2.87</td>
</tr>
<tr>
<td>7</td>
<td>orange</td>
<td>224</td>
<td>124</td>
<td>47</td>
<td>62.06</td>
<td>33.37</td>
<td>56.24</td>
<td>5.35</td>
</tr>
<tr>
<td>8</td>
<td>purpleish blue</td>
<td>68</td>
<td>91</td>
<td>170</td>
<td>40.59</td>
<td>16.15</td>
<td>-45.14</td>
<td>3.53</td>
</tr>
<tr>
<td>9</td>
<td>moderate red</td>
<td>198</td>
<td>82</td>
<td>97</td>
<td>50.58</td>
<td>47.55</td>
<td>15.17</td>
<td>5.52</td>
</tr>
<tr>
<td>10</td>
<td>purple</td>
<td>94</td>
<td>58</td>
<td>106</td>
<td>30.51</td>
<td>25.11</td>
<td>-21.74</td>
<td>1.02</td>
</tr>
<tr>
<td>11</td>
<td>yellow green</td>
<td>159</td>
<td>189</td>
<td>63</td>
<td>72.31</td>
<td>-27.84</td>
<td>57.83</td>
<td>1.01</td>
</tr>
<tr>
<td>12</td>
<td>orange yellow</td>
<td>230</td>
<td>162</td>
<td>39</td>
<td>71.43</td>
<td>15.50</td>
<td>67.80</td>
<td>4.11</td>
</tr>
<tr>
<td>13</td>
<td>blue</td>
<td>35</td>
<td>63</td>
<td>147</td>
<td>29.46</td>
<td>20.74</td>
<td>-49.34</td>
<td>5.77</td>
</tr>
<tr>
<td>14</td>
<td>green</td>
<td>67</td>
<td>149</td>
<td>74</td>
<td>55.26</td>
<td>-41.23</td>
<td>32.03</td>
<td>1.15</td>
</tr>
<tr>
<td>15</td>
<td>red</td>
<td>180</td>
<td>49</td>
<td>57</td>
<td>41.53</td>
<td>52.67</td>
<td>26.92</td>
<td>4.06</td>
</tr>
<tr>
<td>16</td>
<td>yellow</td>
<td>238</td>
<td>198</td>
<td>21</td>
<td>52.41</td>
<td>-18.46</td>
<td>26.64</td>
<td>3.17</td>
</tr>
<tr>
<td>17</td>
<td>magentas</td>
<td>193</td>
<td>84</td>
<td>151</td>
<td>51.74</td>
<td>51.26</td>
<td>-15.48</td>
<td>2.64</td>
</tr>
<tr>
<td>18</td>
<td>cyan</td>
<td>0</td>
<td>136</td>
<td>170</td>
<td>52.41</td>
<td>-18.46</td>
<td>26.64</td>
<td>3.72</td>
</tr>
<tr>
<td>19</td>
<td>white 9.5 (05 D)</td>
<td>245</td>
<td>245</td>
<td>243</td>
<td>96.49</td>
<td>-0.35</td>
<td>0.96</td>
<td>0.84</td>
</tr>
<tr>
<td>20</td>
<td>neutral 8 (23 D)</td>
<td>200</td>
<td>202</td>
<td>202</td>
<td>81.17</td>
<td>-0.69</td>
<td>-0.24</td>
<td>0.92</td>
</tr>
<tr>
<td>21</td>
<td>neutral 6.5 (44 D)</td>
<td>161</td>
<td>163</td>
<td>163</td>
<td>66.84</td>
<td>-0.71</td>
<td>-0.25</td>
<td>1.23</td>
</tr>
<tr>
<td>22</td>
<td>neutral 5 (70 D)</td>
<td>121</td>
<td>121</td>
<td>121</td>
<td>58.86</td>
<td>0.20</td>
<td>-0.55</td>
<td>1.21</td>
</tr>
<tr>
<td>23</td>
<td>neutral 3.5 (105 D)</td>
<td>82</td>
<td>84</td>
<td>86</td>
<td>35.61</td>
<td>-0.36</td>
<td>-1.44</td>
<td>1.58</td>
</tr>
<tr>
<td>24</td>
<td>black 2 (1.5 D)</td>
<td>49</td>
<td>49</td>
<td>51</td>
<td>20.40</td>
<td>0.47</td>
<td>-1.27</td>
<td>1.89</td>
</tr>
</tbody>
</table>

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 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.

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 (=ΔE<sub>ab</sub>)

<table>
<thead>
<tr>
<th>1st R'G'B' data set</th>
<th>2nd R'G'B' data set</th>
<th>Illum. for ΔE&lt;sub&gt;ab&lt;/sub&gt;</th>
<th>avg. ΔE&lt;sub&gt;ab&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>sRGB from L<em>a</em>b* D50 (ColorChecker 2005)</td>
<td>sRGB (GMB) (ColorChecker 2005)</td>
<td>D65</td>
<td>2.64</td>
</tr>
<tr>
<td>sRGB from L<em>a</em>b* D50 (ColorChecker 2005)</td>
<td>sRGB (BabelColor Avg.)</td>
<td>D65</td>
<td>1.30</td>
</tr>
<tr>
<td>sRGB (GMB) (ColorChecker 2005)</td>
<td>sRGB (BabelColor Avg.)</td>
<td>D65</td>
<td>1.95</td>
</tr>
<tr>
<td>Adobe RGB from L<em>a</em>b* D50 (ColorChecker 2005)</td>
<td>Adobe RGB (BabelColor Avg.)</td>
<td>D65</td>
<td>1.30</td>
</tr>
<tr>
<td>Apple RGB from L<em>a</em>b* D50 (ColorChecker 2005)</td>
<td>Apple RGB (BabelColor Avg.)</td>
<td>D65</td>
<td>1.25</td>
</tr>
<tr>
<td>ProPhoto from L<em>a</em>b* D50 (ColorChecker 2005)</td>
<td>ProPhoto (BabelColor Avg.)</td>
<td>D65</td>
<td>1.03</td>
</tr>
</tbody>
</table>

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.
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* 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. 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; 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.

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*, to XYZs
b) XYZs to XYZd (if not the same illuminant)
c) XYZd to RGBd

d) RGBd 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:

\[
X = X_n \left[\left(\frac{L^*+16}{116}\right)+\frac{(a^*/500)}\right]^3 \\
Y = Y_n \left[\left(\frac{L^*+16}{116}\right)^3 \\
Z = Z_n \left[\left(\frac{L^*+16}{116}\right)-\frac{(b^*/200)}\right]^3
\]

where \(X_n, Y_n, Z_n\) 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 \(X/X_n, Y/Y_n, Z/Z_n\) ratios are larger than 0.008856, which is the case for all patches of the ColorChecker.

\[
\begin{bmatrix}
0.0085 \\
0.4323 \\
-0.0085
\end{bmatrix}
\begin{bmatrix}
0.9870 \\
0.4323 \\
-0.0085
\end{bmatrix} = \begin{bmatrix}
R_{dw} / R_{sw} \\
G_{dw} / G_{sw} \\
B_{dw} / B_{sw}
\end{bmatrix}
\]

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 acceptance8 incorporate such a transform. One contender that has withstood critical review 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 standard9. 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:

\[
\begin{bmatrix}
R_{dw} \\
G_{dw} \\
B_{dw}
\end{bmatrix} = \begin{bmatrix}
0.8951 \\
-0.7502 \\
0.0389
\end{bmatrix} \begin{bmatrix}
X_{dw} \\
Y_{dw} \\
Z_{dw}
\end{bmatrix}
\]

(4)

\[
\begin{bmatrix}
R_{sw} \\
G_{sw} \\
B_{sw}
\end{bmatrix} = \begin{bmatrix}
0.8951 \\
-0.7502 \\
0.0389
\end{bmatrix} \begin{bmatrix}
X_{sw} \\
Y_{sw} \\
Z_{sw}
\end{bmatrix}
\]

(5)

\[
\begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix} = \begin{bmatrix}
0.8951 \\
-0.7502 \\
0.0389
\end{bmatrix} \begin{bmatrix}
0.2664 \\
1.7135 \\
0.0129
\end{bmatrix}
\]

(6)

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)_{d} and (RGB)_{s} 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:

\[
\begin{bmatrix}
X \\
Y \\
Z_{\text{dest.}} \\
\end{bmatrix} = \begin{bmatrix}
X \\
Y \\
Z_{\text{source}} \\
\end{bmatrix} \cdot \begin{bmatrix}
Bradford \text{ matrix} \\
3x3 \\
\end{bmatrix} .
\] (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 Televison Engineers. The RGB triads are obtained with the following multiplication, with Y of the illuminant normalized to 100:

\[
\begin{bmatrix}
R \\
G \\
B \\
\end{bmatrix} = \begin{bmatrix}
X \\
Y \\
Z \\
\end{bmatrix} \cdot \begin{bmatrix}
XYZ \rightarrow RGB \text{ matrix} \\
3x3 \\
\end{bmatrix} .
\] (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 Berms, Motta and Gorzynski. Easily readable presentations of gamma can be found in the book and the Internet articles of Poynton, The definition of the various flavors of gamma is well presented in a tutorial that is part of the Portable Network Graphics (PNG) Specification 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 (γ_{file} = γ_{camera} * γ_{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: (γ_{display} = γ_{LUT} / γ_{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 following form:

\[
V = (1 + \text{offset})L' - \text{offset} \quad \text{for } L' \geq L, \geq \text{transition}
\]

\[
V = \text{slope} \times L \quad \text{for } \text{transition} > L, \geq 0
\] (9)
where \( L \) is the image luminance \((0 \leq L \leq 1)\) 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:

\[
\begin{align*}
\text{offset} &= 0.055 \\
\gamma &= 0.42 \\
\text{transition} &= 0.003 \\
\text{slope} &= 12.92
\end{align*}
\]

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 \((1 + \text{offset})\) 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:

\[
V = L^\gamma \quad \text{for } 0 \leq L \leq 1 ,
\]

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):

\[
\begin{align*}
R' &= \text{round}\left(255 \times \left(1 + \text{offset}\right) \times R^\gamma - \text{offset}\right) \\
& \quad \text{for } 1 \geq R \geq \text{transition} ,
\end{align*}
\]

\[
\begin{align*}
R' &= \text{round}\left(255 \times \text{slope} \times R\right) \\
& \quad \text{for } \text{transition} > R \geq 0 ,
\end{align*}
\]

or:

\[
R' = \text{round}\left(255 \times R^\gamma\right) \quad \text{for } 0 \leq R \leq 1 .
\]

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 \((R', G', \text{ and } B')\) have to be normalized between 0 and 1 prior to this operation:

\[
\begin{align*}
R &= 255 \times \left(\frac{R' + \text{offset}}{1 + \text{offset}}\right)^{1/\gamma} \\
& \quad \text{for } 1 \geq R' \geq \text{transition x slope} ,
\end{align*}
\]

\[
\begin{align*}
R &= 255 \times \frac{R'}{\text{slope}} \\
& \quad \text{for } \text{transition x slope} > R' \geq 0 ,
\end{align*}
\]

or

\[
R = 255 \times R^{1/\gamma} \quad \text{for } 0 \leq R' \leq 1 .
\]

**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 \((\gamma_{\text{Mac}} \times \gamma_{\text{LUT}})\) 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):

\[
L = \left(\frac{V + \text{offset}}{1 + \text{offset}}\right)^{1/\gamma} .
\]

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

\[
L = V^{1/\gamma} .
\]

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 $\gamma_{LUT}$ 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.

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. confirms that this procedure maximizes the color gamut.

Berns & al. 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:

$$\gamma_{overall} = \frac{\gamma_{file} \times \gamma_{LUT}}{\gamma_{CRT}}.$$  \hspace{1cm} (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* 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):

$$L^* = 116(Y/Y_n)^{1/3} - 16 \quad \text{for} \quad Y/Y_n > 0.008856$$

$$L^* = 903.3(Y/Y_n) \quad \text{for} \quad Y/Y_n \leq 0.008856$$

$$a^* = 500[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}]$$

$$b^* = 200[(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}]$$  \hspace{1cm} (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:

$$\Delta E_{ab}^* = \left[ (\Delta a^*)^2 + (\Delta b^*)^2 + (k\Delta L^*)^2 \right]^{1/2},$$  \hspace{1cm} (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 $\Delta E_{ab}=1$ 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. We will nonetheless evaluate the conversion

<table>
<thead>
<tr>
<th>Processing step</th>
<th>Average $\Delta E_{ab}$ error</th>
<th>Standard deviation</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bradford matrix</td>
<td>1.4</td>
<td>0.9</td>
<td>Measured for a D65 to D50 conversion. From Ref. 18.</td>
</tr>
<tr>
<td>XYZ to RGB (matrix)</td>
<td>$\approx 0$</td>
<td>$\approx 0$</td>
<td>Negligible error when constants with at least 4 significant decimals are used.</td>
</tr>
<tr>
<td>XYZ to RGB (clipping)</td>
<td>variable</td>
<td>variable</td>
<td>See text.</td>
</tr>
<tr>
<td>RGB to R’G’B’ (simple vs. detailed gamma)</td>
<td>1.3</td>
<td>0.92</td>
<td>When a simple gamma expression is used instead of a detailed one (when available). Measured for sRGB.</td>
</tr>
<tr>
<td>RGB to R’G’B’ (rounding error)</td>
<td>0.23</td>
<td>0.11</td>
<td>Typical values. Values are slightly higher for larger spaces (Ex: 0.28 average for Adobe (1998)).</td>
</tr>
</tbody>
</table>

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. 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. 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
development 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

<table>
<thead>
<tr>
<th>Processing steps</th>
<th>Average ΔE*ab error</th>
</tr>
</thead>
<tbody>
<tr>
<td>L<em>a</em>b* to XYZ</td>
<td>0</td>
</tr>
<tr>
<td>Bradford matrix: XYZD50 to XYZD65</td>
<td>1.4</td>
</tr>
<tr>
<td>XYZ to RGB: matrix math.</td>
<td>0</td>
</tr>
<tr>
<td>XYZ to RGB: clipping</td>
<td>Not included</td>
</tr>
<tr>
<td>RGB to R’G’B’: detailed gamma</td>
<td>0</td>
</tr>
<tr>
<td>RGB to R’G’B’: R’G’B’ rounding</td>
<td>0.23</td>
</tr>
<tr>
<td><strong>Combined RSS error</strong></td>
<td>1.42</td>
</tr>
</tbody>
</table>

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.

RGB spaces could degrade the color fidelity to a point where
it could be noticed.

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:

\[
RSS \_ error = \left[ (error\# 1)^2 + (error\# 2)^2 + \ldots + (error\# n)^2 \right]^{1/2}
\]  

(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., 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 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 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
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.

Special thanks to all who have provided measurement data used for the spectral average numbers presented here, and to those who have helped with their comments and suggestions.

---

About the author

Danny Pascale, M.Sc.A., B.Ing.: With many years of experience in all aspects of Research and Development projects, he now does technology assessment and helps companies bring new products into the market in the computer and consumer electronics sectors. He founded The BabelColor Company in 2003, dedicated to the development of colorimetric tools, and which also offers color measurement and translation services. He is a member of SPIE, OSA, and IEEE.
References

1 ColorChecker, product No. 50105 (Standard) or No. 50111 (Mini), manufactured by the Munsell Color services laboratory of GretagMacbeth.
4 ColorChecker reference data is available from GretagMacbeth at the following Web site: http://usa.gretagmacbethstore.com.
   “Frequently Asked Questions About Gamma,” available as “GammaFAQ.pdf”;
   “The rehabilitation of gamma,”
   available as “Rehabilitation_of_gamma.pdf”;
   “Frequently Asked Questions About Color,”
   available as “ColorFAQ.pdf”.
16 From Ref. 11. The gamma function of that reference is defined with a different equation than the one used in this document. The gamma curve of the reference was regenerated and fitted against the detailed gamma function defined in this document.
18 The method is described in Ref. 9. The results are from the slide presentation at the conference.