TUTORIAL - Color Management for your camera, monitor and printer
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My photographer friends know how to profile cameras and monitors, but they still have questions about how to use the resulting profiles and what principles are involved. This tutorial is not so much a "how to" session, but rather a brief explanation of how color management systems work.

The goal of any color management system is to arrange things so that a scene captured by a camera and displayed on a monitor or a print will maintain the same appearance. We hope to achieve this uniformity by means of instrument calibration and profiling:

Calibration: Setting instrument parameters to change performance. On a monitor this refers to white balance, luminance, and gamma.

Profiling: Recording instrument performance and tabulating or encoding it for use in translating signals.

All decisions in this area depend on human perception of brightness, color, and image quality, so I will begin with characteristics of human vision.

Vision and perception: Our perception of color is the creation of our brain in response to the stimulation of the three types of cones in our eyes. Everything in color management theory is based on the psychophysics of human color perception. This process was quantified in 1931 by the International Commission of Illumination (CIE). The result was a set of curves to represent the sensitivity of the cones of the **standard (colorimetric) observer**. These curves are shown in Fig. 1.

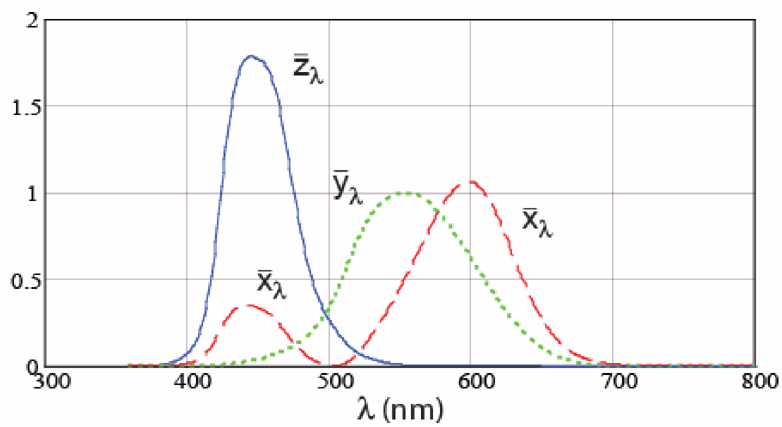

Figure 1: CIE (1931) color matching functions for the standard observer.

These curves are useful because they provide the "primaries" for a **device independent** color space that can be used to correlate our input (camera and scanner) and output devices (monitor, printer, projector). This is the basis of the entire color management system, so please bear with me a bit longer.

The device independent chromaticity diagram: The CIE color matching curves serve to define the CIE xyZ chromaticity diagram that illustrates all colors that can be perceived by the standard observer. The cone responses are denoted by X (red), Y (green), and Y (blue) and the diagram uses the ratios x = X/(X+Y+Z), y = Y/(X+Y+Z), and z = Z/(X+Y+Z) for convenience. Note that x + y + z = 1 and all that we need to plot is y versus x. The CIE xyZ diagram is shown in Fig. 2.

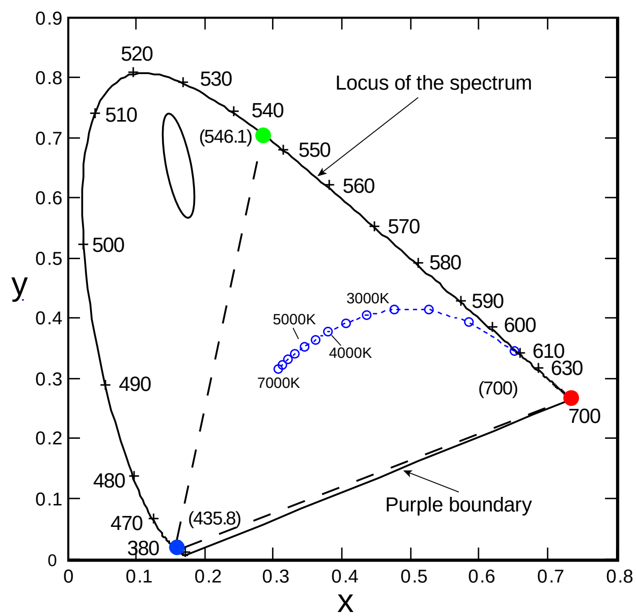

Figure 2: The CIE chromaticity diagram with the RGB color space.

On this diagram stimulation of the x-cone (red) alone would appear off scale at x = 1, y = 0, stimulation of the y-cone (green) alone would appear off scale at y = 1, x = 0, and the z-cone alone would appear at x = 0, y = 0. In the real world these isolated responses are impossible to achieve since a stimulus anywhere in the visual region from 400nm to 700nm will excite more than one type of cone. The colors accessible to the human eye appear inside the spectral curve in Fig. 2 where points on the spectra curve correspond to points in the spectrum of sunlight. Everything outside the spectral curve is “imaginary.”

The three dots at 380 nm, 540 nm, and 700 nm represent light sources that can serve to define a **color space**. With this particular choice of color primaries, only the colors inside the dotted triangle can be represented. Other choices of primaries define Adobe RGB, sRGB, and ProPhoto color spaces. Each choice of color space will cover a somewhat different area in the chromaticity diagram and will represent a particular color with a different set of RGB numbers.

The color management system: For properly calibrated instruments, this is the way the system works. An input device such as a camera presents a set of numbers to represent a particular color in a pixel. The set will specify red, green, and blue based on some set of unknown color primaries such as the spectral profiles of the filters in the Bayer array on the camera sensor. We must determine where this particular color appears on the CIE chromaticity diagram.[1] A good camera profile will specify where any color detected by the camera sensor should appear on the diagram. Output to a display device is just the opposite. We will have some color on the CIE diagram that is specified by a set of primary colors RGB in some color space, say ProPhoto. We need a profile of the monitor so that the software will know what set of input numbers for the monitor will match or at least approximate the color specified by RGB on the CIE diagram.

Calibrating/profiling the monitor: Since image examination requires a monitor we should begin with monitor calibration and profiling. Instrument and software packages accomplish both of these operations, and as a first step we are asked to specify luminance, white balance, and gamma for monitor calibration. Next comes the selection or creation of a profile. Modern LCD monitors with HDMI input support sRGB and some other color spaces, but we want to do better than that. We know that each set of RGB inputs between 0 and 5 volts (16-bit) produces a distinct color on the screen, but the location of this color on the CIE chromaticity diagram is not known. At this point we need either a spectrophotometer or a colorimeter. A spectrophotometer measures light intensity on the screen at many frequencies across the full spectral range to record the spectrum. The corresponding x, y, and z coordinates for the CIE diagram must then be computed from the spectral curve. This computation involves the combination of the recorded spectrum with the CIE matching color functions in Fig. 1. The colorimeter appears to be simpler because there are three sensors fitted with color filters so that their response will be proportional to that of a CIE standard observer. The colorimeter RGB output immediately gives a location in the CIE diagram.

The X-Rite Colormunki is a spectrophotometer while DataColor Spyder 3 is a colorimeter. Either a spectrophotometer or a colorimeter can be used to calibrate a monitor screen or reflected light from a print, but there is controversy about which is best. Proponents of the colorimeter claim that it is better for dark areas since light from a large region of the spectrum is collected for each sensor so that noise is reduced compared with a spectrometer where each color channel covers only a small spectral range. I think either can do a good job and will be much better than no calibration at all.

The calibration/profiling procedure requires mounting the detector on your monitor as illustrated in Fig. 3 with the Spyder 3. First the monitor is calibrated to

Figure 3: A Datacolor Spyder 3 in position on a monitor (from a Datacolor website).

user specified values and then the program causes a series of colors to be displayed. The emitted light is detected and recorded; and at the end of the series, a monitor profile is computed and loaded on the computer so that it can be installed on startup. This process should be repeated every few weeks as the monitor colors and luminance can drift; otherwise we do not need to be concerned with the monitor color space. It does not dictate the choice of working color space in photo editing programs such as Photoshop and Lightroom.

Profiling the camera: The typical digital camera uses a set of color filters in front of the pixels to establish the red, blue, and content of a scene. For example the transmission profiles for the filters used in the Leica M8 are shown in Fig. 4.

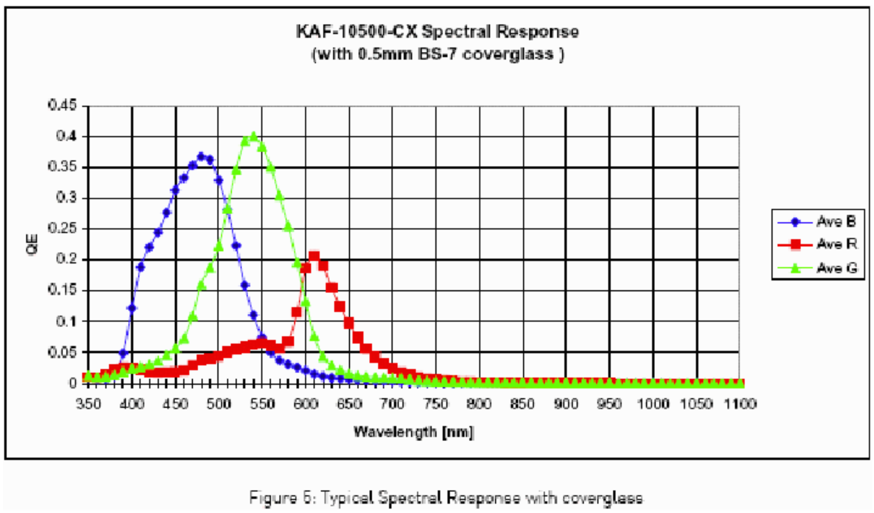

Figure 4: Spectral response of the Kodak sensor used in the Leica M8. (Used with permission)

If these curves were identical in shape to the CIE color matching function shown in Fig. 1, the camera would act as a colorimeter, and the uncorrected RGB response numbers would specify a point in the CIE chromaticity diagram. However, they are different and the construction of a camera profile is necessary.

The way to make a profile is to photograph a color chart (Fig. 5) where the CIE color coordinates of the patches are known. The next step is to analyze the resulting image to correlate the RGB values reported by the camera with the device independent diagram. A particularly convenient choice is the X-Rite ColorChecker card with a plugin program for Adobe Lightroom. One simply selects an image containing the color checker and clicks on export with preset - ColorChecker. The camera profile is computed if the chart image is properly exposed, and the user names the profile. When other images from the same camera are developed in Lightroom,

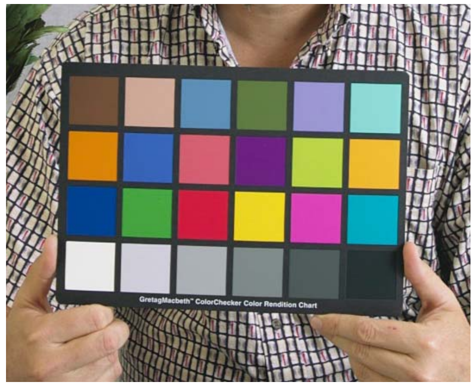

Figure 5: Gretag–Macbeth ColorChecker color chart being held in a portrait setting. (en.wikipedia.org, image by Richard F. Lyon)

the user can click on camera calibration and select the profile pull down. A number of Adobe profiles as well as the user created profiles will be visable. The differences are obvious in the image when different profiles are selected. I find that my profile for the Canon 7D in daylight is fairly close to the Adobe Standard Profile but considerably different from some of the others. Those concerned about accurate color rendition will want to make separate profiles for daylight, flash, high ISO, *etc.*

Profiling the printer: The printer is another output device; and, therefore, profiling is similar to that for the monitor. However, with ink jet printers there are no calibration parameters to set. Color laser jet printers may require calibration procedures. In any event, signals from the computer to the printer cause a particular combination of inks to be to be printed on a particular type of paper, but without a profile we so not know how the color in the finished print will be related to the CIE chromaticity diagram. Fortunately, profiles are available from printer and paper manufacturers for many printer-paper combinations; and you may find that some of them are completely satisfactory for your purposes. Also, pre-made and custom (from user produced prints) can be ordered from photolabs online.

The printer is often the limiting device in color rendition because its gamut of colors is more limited than that of cameras or monitors. If the ProPhoto color space is used in Photoshop or Lightroom to quantify the CIE diagram, it is sure that the printer will not be able to reproduce all the colors that are represented. Printers are getting better and some of them have eight, ten, or even more colors of ink counting black and shades of gray; so good profiles are required and also some decision must be made about what to do with colors that are out of the gamut of the printer. A **rendering intent** is a setting that specifies how to handle out of gamut colors in going to a smaller color space. In the CIE system there are four: **perceptual**, **saturation**, **relative colorimetric**, and **absolute colormetic**. Perceptual and Relative are the choices offered in Lightroom. Peceptual preserves color appearance by adjust all of the colors while preserving their relationships so that they fit the smaller gamut, while Relative maps white of the source to the white of the destination (paper) and clips off all out-of-gamut colors. Perceptual is probably a better choice when many colors are out-of-gamut for your printer.

In some cases printer profiles are not available or perhaps are not very good. Here again we can use our spectrophotometer or colorimeter to determine the profile for a given paper. In this case the software supplied by the manufacturer causes the printer to produce patterns of color. As shown in Fig. 6 the user samples a large number of patches

Figure 6: Image of a Colormunki in action from images.macworld.com

so that the program will have enough data to generate a profile. When an image is printed, the user selects the printer profile and the rendering intent.

One other point needs to be made. In recent versions of Photoshop the user can view the effects of printer profiles and rendering intents on images. The path View > Proof Setup permits a profile to be selected so that color changes and the effect of paper color can be viewed. This soft-proof option is not yet available in Lightroom.

Conclusion: This is my take on color management. I profile my camera, and I think that makes a relatively small difference. I calibrate and profile my monitor (Dell 20" Ultrasharp 2007FP) and that makes a lot of difference. The displayed luminance is very important. Thus far, I have only used canned printer profiles from Canon, Red River, and Ilford with my Canon i9900 and Pro 9500 printers.

I welcome your comments and corrections.

Notes:

1. One problem with the CIE diagram is that at a given point in the visual region the perception of color change is not the same for movement in all directions. This effect is illustrated by the ellipse (Fig. 2) inside which the standard human observer perceives little difference in color. There are a number of ways to transform (re-plot) the data to obtain perceptional uniformity so that color change is proportional to distance moved in any direction. CIE LAB is a popular color model that achieves better uniformity. For more complete discussions see: C.S. Johnson, Jr., *Science for the Curious Photographer* (A.K. Peters, Natick, 2010) Chap. 15 and Fraser, Murphy, and Bunting, *Color Management* (Peachpit Press, Berkeley, 2005). Wikipedia.com is also a source for many of the topics mentioned here.