Photocolorimetry

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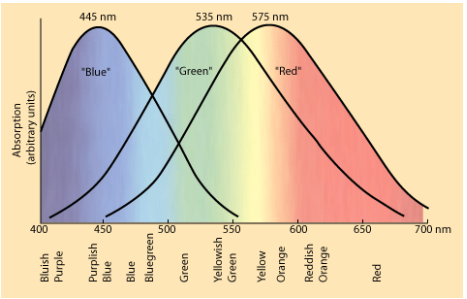
Traditionally, colorimetry has used spectrophotometry, which measures the energy present over a range of wavelengths, as the spectral power distribution (SPD). This approach can be complicated and impractical in some cases, so for many applications, tristimulus colorimetry is used for approximating the SPD of self-luminous sources, however it still requires delicate and complex instrumentation. The third sort of colorimeter is sometimes referred to as "image-taking colorimetry", and this is the methodology (photocolorimetry) explored in this article.

Photocolorimetry is the measurement of color from digital images. This is a newly emerging methodology, made possible by recent improvements in digital camera technology.



Digital cameras record color in a 3-space, typically a specific type of Red-Green-Blue (RGB) space, such as sRGB (standard RGB for internet) or Adobe RGB (has a wider gamut or range of possible colors). These three dimensions correspond to the three color-specific types of cones in the color-sensitive eye. Cones are photo-receptors of 3 types, each one having maximum sensitivity at the red, green, and blue wavelengths. Some eyes have been found to have a fourth type of cone, one that is maximally sensitive to UV band light (ultraviolet 357-367 nm). Marsupials, some reef fish such as the damselfish, most birds and reptiles, and some people (tetrachromats) have this extra fourth channel of light information.

The colors of the visible light spectrum

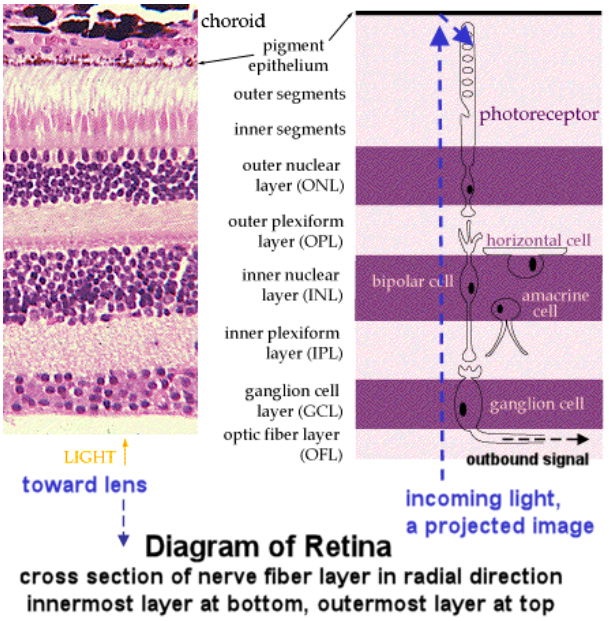
color	wavelength interval	frequency interval
red	~ 625–740 nm	~ 480–405 THz
orange	~ 590–625 nm	~ 510–480 THz
yellow	~ 565–590 nm	~ 530–510 THz
green	~ 500–565 nm	~ 600–530 THz
cyan	~ 485–500 nm	~ 620–600 THz
blue	~ 440–485 nm	~ 680–620 THz
violet	~ 380–440 nm	~ 790–680 THz

Wavelengths and Frequencies. Notice that the visible band is about 1 octave, ranging from 400 to 800 nm (or 800 to 400 terahertz).

When working with images for luminous display, RGB is a good match to the human visual system.

Vision

Cones are arrayed in the retina of the eye with the photosensitive end pointed at the choroid, which is the interior wall of the globe of the eye; they respond to light reflected off of the pigmented epithelium. The incoming image formed by the lens and pupil is brought to a focus on this reflective layer, with the incoming light in effect being projected onto a screen as a way of creating the image, with the cones each pointing at a small "pixel" of the projection screen. To extend the analogy, the eye is like an OmniMax movie theater with images projected onto a spherical screen, and with each photoreceptor like the moviegoer, except it's transparent and so close to the screen that only a small area is visible. The configuration of the retina lining the projection screen requires the entire photosensory transducer/signal-processing/routing system to be practically transparent so as not to distort the incoming image.



Photomicrograph (L) and schematic diagram (R) depicting the layers of the retina. The retina is about 0.5 mm in thickness, and the choroid layer (containing the vascular supply vessels) just peripheral to the retina is also about 0.5mm thick. The retina is transparent and includes the specialized cells for light detection, filtering, transduction, and conductance to central nervous system.

Pigmentation

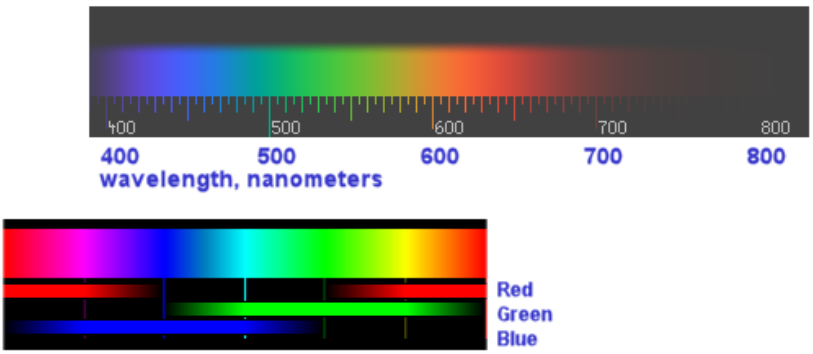
This system would not be possible without pigments. The photo-chemico-electrical response of the photoreceptor depends on the pigment rhodopsin (visual purple), and the 3 wavelength-sensitive photopsins. The formation of the image depends on the pigment epithelium to create a reflective screen. The pigment epithelium is the

dividing surface between the retina and the choroid; the choroid has blood vessels to supply the cellular nutrients. Pigment appears to be associated with blood, but melanogenesis is not a fully understood process.

Vision and the collecting of light images requires the *absence* of pigment in much of the ocular anatomy, especially the retina, lens, and cornea, which is itself a lens, having the most optical power of the entire system, since it has the air/water interface. Since blood is non-transparent, the cornea and lens (and other ocular media) must be avascular tissue (like the retina, but not even adjacent to vasculature), requiring a different nutrient delivery mechanism. For the transparent ocular segments, the nutrients are delivered via the aqueous humor, a clear watery fluid produced behind the peripheral iris and draining in front of the peripheral iris. The continuous production and draining of the aqueous humor creates an intraocular pressure (IOP) of about 20 mmHg. Glaucoma consists of events surrounding the failed regulation of the gauge pressure of the ocular globe (IOP), leading to damage of the delicate nerve fiber layer.

Pigmentation via melanization has a central role in biological coloration. Pigmentation also constitutes much of what creates color variations, and they do this by subtracting complementary colors. The Cyan-Magenta-Yellow-Black color space, as a system for printing with pigments, complements the RGB color space as a system for mixing light sources.

Another type of color is structural color – color that is not due to pigment but rather to molecular textural properties at the level of light wavelength (half a micron or so). For example the sky is blue for the same reason some eyes are blue: the Tyndall effect (Rayleigh scattering) of the shorter wavelengths being reflected back more than the longer wavelengths. There is no "blue pigment" in the sky or the blue iris. Bird feathers that appear blue or iridescent show this color due to diffraction effects produced by the feather's ultrastructure. The rainbow pattern seen on a CD is another example of structural color.



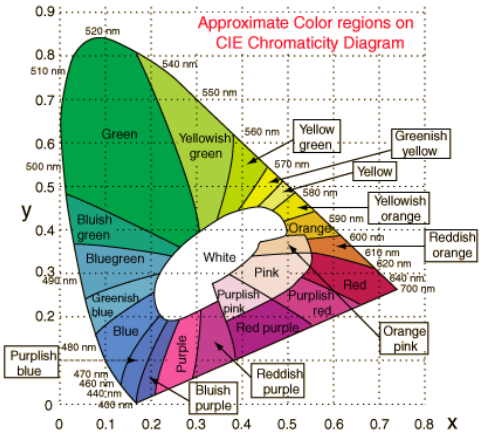
Comparison of visible light spectrum and RGB spectrum

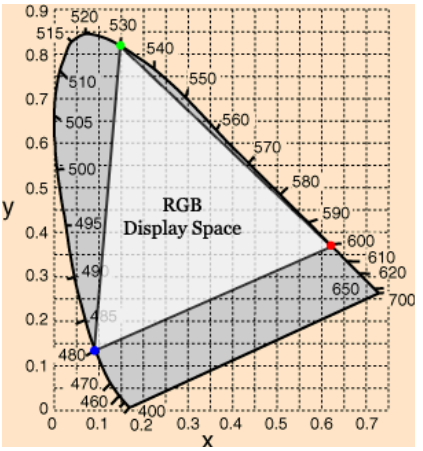
CIE Color Spaces

Color descriptions have been standardized with these attributes as defined by the CIE recommendations (CIE is Commission Internationale de l'Eclairage). The recommendations of the CIE are as follows:

Brightness. The attribute of a visual sensation according to which an area appears to exhibit more or less light.
Hue. The attribute of a visual sensation according to which an area appears to be similar to one, or to proportions of two, of the perceived colors red, yellow, green and blue.
Colorfulness. The attribute of a visual sensation according to which an area appears to exhibit more or less of its hue.

The following figure on the left illustrates the x-y chromaticity coordinates that were developed by CIE. Note that the perimeter spans the range of wavelength approximations, except for the transition zone red/purple/blue. The points along this perimeter curve are known as monochromatic colors since they have a theoretically pure single wavelength. Also note that there are specific names for colors falling within specific ranges of chromaticity. In other words, qualitative attributes such as "yellowish orange" correspond to a very well defined range of colors; this is the quantification of the qualitative.

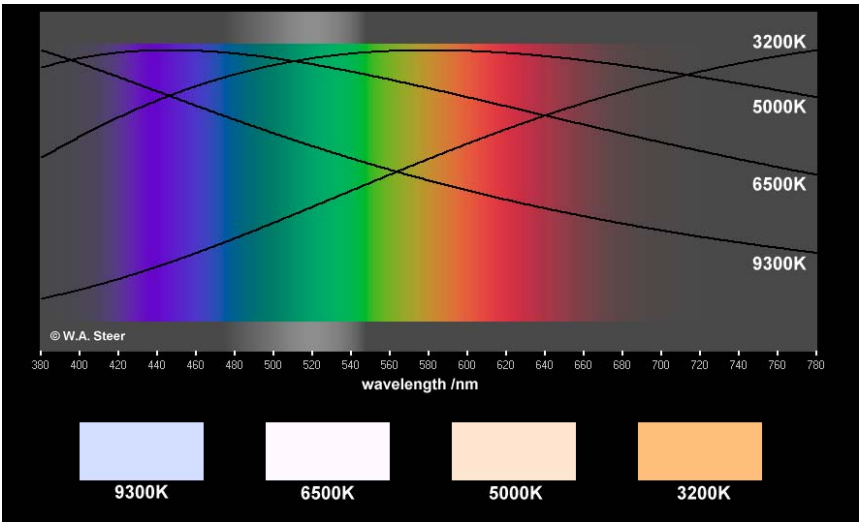




The right figure illustrates how the range of colors that can be specified via the RGB coordinate system is a subset of the range of visible colors.

Illuminant Standardization

Apparent color will depend on the spectral content of the source illumination. The CIE standard illuminants include D50, D55, D65, or D75. D65 corresponds to illumination light at 6500 K temperature, equivalent to noontime daylight. Daylight is typically in the range of 5500 to 6000, and an electronic flash (xenon strobe) emits light at 5500 K typically. Incandescent lamps are in the range of 2800 to 3300 K.



Spectral Energy Density

$$U(\lambda,T) = 8\pi hc\lambda^{-5} / \left(e^{hc/\lambda kT} - 1 \right)$$

where

λ is the wavelength, in metres

T is the temperature in Kelvin

$h = 6.626\times10^{-34}$ J·s [Planck's constant]

$k = 1.381\times10^{-23}$ J·K^{-1} [Boltzmann's constant]

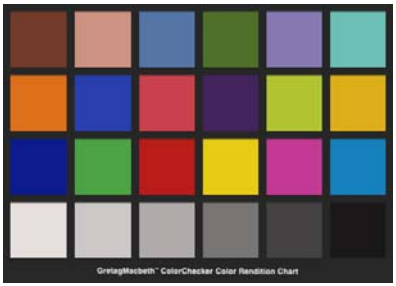
$c = 3.0\times10^{8}$ m·s^{-1} [speed of light]

Colorimetry from digital imaging requires measuring, controlling, and calibrating the color characteristics of all elements in the imaging system. The ideal illumination source is electronic flash with no ambient light, since this has a constant color temperature.

Any photogrammetric color measurement will also be influenced by the optical characteristics of the lens (collecting optics) and the imaging sensor (camera operating characteristics). With the high quality photographic lens commonly available, the color is least influenced by this factor, but imaging sensors have wide variations.

Color Checker

To measure the recording fidelity of the color of reflected light, a common method is to photograph a color checker under controlled illumination, and then measure the image data and compare to a reference standard from the manufacturer of the color checker. The color checker is a card with calibrated tiles that have various shades of color at a sampling of points in the CIE color space. For each tile, the RGB, LAB and xy coordinates are specified. Error intervals for each color are typically presented in the LAB color space, since the Euclidean distance between observed and expected values corresponds to apparent visual difference. For estimating apparent color differences, the LAB color space is used with a scaling so that 1.0 units corresponds to a just noticeable difference (JND).

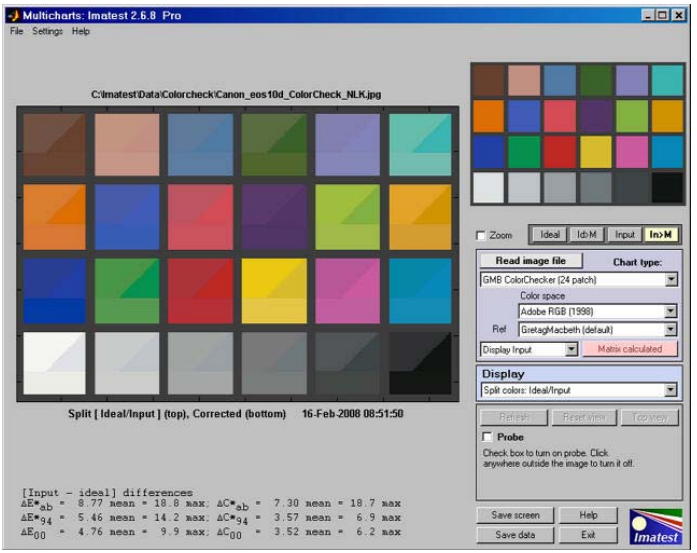


1. dark skin	2. light skin	3. blue sky	4. foliage	5. blue flower	6. bluish green
7. orange	8. purplish blue	9. moderate red	10. purple	11. yellow green	12. orange yellow
13. blue	14. green	15. red	16. yellow	17. magenta	18. cyan
19. white (.05)	20. neutral 8 (.23)	21. neutral 6.5 (.44)	22. neutral 5 (.70)	23. neutral 3.5 (1.05)	24. black (1.50)

GretagMacbeth Color Checker and color names.

The card from GretagMacbeth is one commonly used color checker, and the error in recorded color values is determined by software such as Imatest (www.imatest.com).

Output from the measured color error is typically presented in terms of the LAB color space, as displayed and described below.



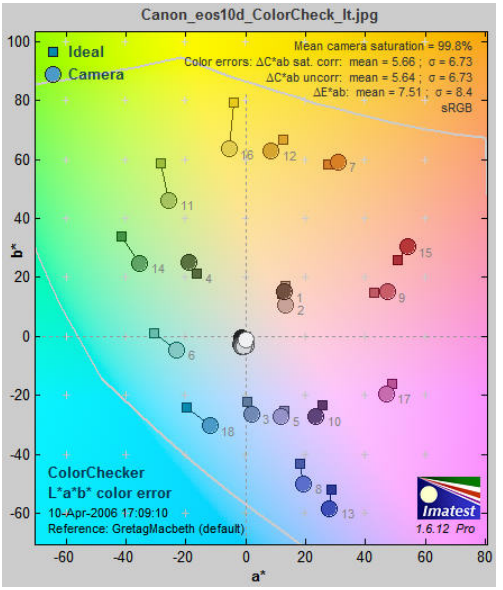
L*a*b* and RGB values for known color spaces are used in the Imatest analysis. (sRGB is the RGB standard color space for website display.) *xy* chromaticity values (from the 1931 chart) are far from perceptually uniform, i.e., distances between points on the *xy*-plane are not proportional to perceptible differences between colors (green is greatly exaggerated). Color differences are better represented in the CIELAB color space, where L* is luminance, a* is color on a green-red scale, and b* color on a blue-yellow scale. A distance of 1 between L*a*b* values represents the minimum perceptible difference (just-noticeable difference, JND) between colors (for relatively unsaturated colors). For colors on the a*b* plane (neglecting L*), this distance is expressed by the equation,

$\Delta C^* = ((a_2^*-a_1^*)^2 + (b_2^*-b_1^*)^2)^{1/2}$; where $(...)^{1/2}$ denotes square root.

More generally,

$\Delta E^*_{ab} = ((L_2^*-L_1^*)^2 + (a_2^*-a_1^*)^2 + (b_2^*-b_1^*)^2)^{1/2}$ (includes L^* differences)

Although ΔC and ΔE^*_{ab} (which are both Euclidian distances) are widely used to quantify color differences, they are not as accurate as the CIE 1994 and CMC equations…



In this figure, a square symbol is plotted where each of the 24 colors are specified, and the circle symbol represents the color coordinates as measured from the image data (square=ideal, circle=camera). The length of the line connecting these points corresponds to the color error. The six gray levels in row 4 of the color checker appear at the center of this color plot, where a=0 and b=0. This example is from a test of the Canon EOS 10D.

Use of LAB Color Space for image correction

Dan Margulis has been pioneering photographic image enhancement methods using the LAB color space for several years. LAB conventionally refers to the L*a*b* coordinate system for representing color tone as Lightness plus two color parameters. He recommends working in all channels (RGB, CMYK, LAB) but for different objectives.

In Professional Photoshop: The Classic Guide to Color Correction (5th Edition), Margulis writes "Every image file has 10 channels; CMYK, LAB, and RGB each have strengths and weaknesses. We need to learn not just to work in all three—but to think in them." The various color spaces are each useful for distinct purposes.

"When making this choice-of-colorspaces decision, the possibilities are three:

- It makes no difference. Example: setting highlight and shadow. All three color spaces do this well.

- One or more color spaces has technical advantages that may or may not have any real impact. Examples: curves to increase contrast in localized areas, which often are better in CMYK; sharpening, which is occasionally superior in LAB.
- Clear reasons exist to prefer one color-space. Examples: channel blending … which should definitely be done in RGB rather than CMYK, and the black blob of the following exercise, where CMYK is clearly the tool of choice, even if your final goal is an RGB file."

A correction curve can be developed from the camera calibration for a specific illumination/lens configuration and then applied to images of color samples to be measured.

Color Management

Color Management refers to the control of variations in color at all points along the workflow, from imager to file formats, to monitors and printers. Every step along the way needs to be controlled carefully so as to avoid distortions. The problem is illustrated when going to any electronics store that has television sets lined up – they all show slightly different color tones in presenting the same program. For measuring and correcting monitor and printer color, devices such as Spyder from ColorVision (www.colorvision.com) are useful.

Imaging Advances

As current generation digital cameras such as the $500 10-megapixel Nikon D40X or the $1700 12-megapixel Nikon D300 become increasingly precise, with 14-bits per channel recording and multiple color spaces to select from, the trend is clear that photocolorimetry will find many new applications.

It is being used to measure the anthocyanin content of pomegranate jelly, for example – all from trichromatic data. Digital image data is relatively simple to acquire and process, and the studies have shown that optical properties of food products are correlated to nutritional content and freshness.

Photocolorimetry is being used at the University of Michigan to measure tooth whiteness for matching replacement teeth.

With iris recognition becoming popular for biometric based authentication, more research has been focusing beyond the infrared channel traditionally used for collecting image data and recent work has sought to characterize the spectral content of the iris tissue, using infrared as well as RGB (4-channel colorimetry).

Measuring skin color and eye color has been the focus of recent research in the genetics of pigmentation, with recent studies from Dr. Esteban Parra of the University of Toronto, who is using a specialized camera I developed specifically for biometric assessment of iris color. I have also been developing cameras for measuring hand color and geometry, as well as dermatoglyphics (fingerprints and palm prints), all of which can be imaged quite well using digital SLR cameras.

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