Color and Calibration

(*and the Secret Slider*)

Robert Stone - v5.2 - December 2023

Lightroom, Adobe Camera Raw and Photoshop have an abundance of tools that photographers can use to modify color. Some tools affect the character of light (warm, cool), some affect specific hues (red, green, blue), and some can be directed to shadows, mid-tones or highlights. Lightroom (LR) and Adobe Camera Raw (ACR) have panels (Color Mixer in ACR, HSL/Color in LR) with 20+ color-related sliders, and a panel for Color Grading with complex color wheels. The number of choices is intimidating. Some of these sliders are identified by color (red, orange, purple, green, etc.), others are identified by color attribute (hue, saturation, lightness).

You may ask yourself why you need so many options. Shouldn't the computer images and prints look just like the previews I see on the camera? Generally, they should. But color adjustments can make the image better. Making a formal portrait warmer or cooler can have an enormous effect on the emotional Impact of the image.

The Calibration panel seems to have been 'discovered' on YouTube recently and is now frequently mentioned as part of image editing. It certainly seems simpler, with only 6 sliders for the hue and saturation of the three primary colors (Red, Green, and Blue) and one rather curious slider for 'Shadow Tint'. (Spoiler Alert: Alister Benn's[1] Secret Slider is on this panel but it's not the Shadow Tint slider.)

That said, photography has a color problem. Film, digital sensors, color displays and printing inks do not 'see' color the way the human eye sees color! Each camera/sensor manufacturer's filter colors (e.g. Bayer and RGBE filters, and others[2]) will be slightly different. Every computer display uses different LEDs or phosphors to produce color. Each printer model may use a unique set of ink colors. Every step in the image processing 'pipeline', camera, computer, printer brings its own set of color biases to the finished product. (You can add projectors and scanners to this list, too. Even lenses can add color tints.)

Getting colors that match what you see on the camera's LCD or computer screen is a complex problem typically addressed by engineers, color experts and chemists. Manufacturers often seek a 'signature' color rendition across their entire line of cameras. But the choices made by engineers, color experts and chemists may not be your choices. Tools like Photoshop, Adobe Camera Raw and Lightroom give the photographer a way to adjust colors, and to use color to enhance an image's emotional impact.

The Calibration Panel works differently than the other color panels. This changes how and when it should be used when editing and adjusting color.

The Color Problem

It's actually quite surprising that all these potential color issues can be resolved. The issues are complex in terms of biology, physics, and chemistry, but completely manageable in practice. Every device in the image pipeline, camera, display, printer, can be color *calibrated.* That is, the wavelength and intensity of color are measured, then *profiled* so colors on one device will match colors on another device. These device profiles do most (but not all) of the color management work to make image colors look correct from start to finish. LR, ACR, and PS are all 'profile aware'.

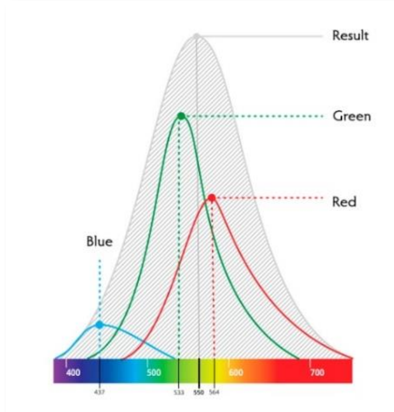
[1] Alister's YouTube channel: Expressive Photography.

[2] Wikipedia article on Color Filter Arrays.

Let's take a look at how human vision works, and how hardware devices manage color.

Color Vision & Color Theory

Color is all about biology. There are two types of light sensitive cells in the retina, rods and cones. The rod cells work better at low levels of light but are only weakly affected by color; our night vision is not very colorful.



The cone cells, sensitive to different wavelengths of light, work best at day-normal light levels. The three types of cone cells give us the three 'primary' colors, Red, Green and Blue, that we call 'trichromatic' vision. The graph at right shows how the three cone cells respond to different wavelengths of light.

All three types of cone cells respond to a broad range of wavelengths, the well-known 'bell shaped curve'. Each has a peak of sensitivity at a specific wavelength. We commonly refer to the three different cone cells as Red, Green and Blue, but this is not true. The red cones peak in the reddish-yellow area, green cones peak a yellowish green, the blue cones really do peak in blue.

Biologists will refer to the three cone types as L, M and S for Long, Medium and Short wavelengths.[3] I will continue to refer to the cones as Red, Green and Blue, but importantly all cones respond to a broad section of the spectrum. Note that the blue cones are less sensitive to light than the others.[4]

Our true RGB vision is actually the result of additional 'signal processing' in the Ganglion[5] layer of the retina brain according to differences between the three color cone cells. The optic nerve passes information to the visual cortex of the brain via the thalamus. [6] Only then do we fully recognize red, green and blue.

A physicist thinks of colors as a short range of wavelengths (or frequencies) of electromagnetic energy. The full electromagnetic spectrum runs from short wavelength, high frequency (and highly dangerous) gamma rays to extremely long wavelength, low frequency radio waves. Our 'visible spectrum' colors are in an energy range that only modestly jiggle the pigments in the retina. We cannot see color beyond the ultraviolet or infrared; the retinal pigments simply do not respond in a meaningful way.

Color perception is entirely due to the sensitivity of the different retina pigments to different wavelengths, and the signals sent to the brain. Mutations in retinal pigment genes change how the pigments respond to light and may cause various forms of color blindness. These genes are on the X chromosome. Since men have only one X chromosome, color blindness is more prevalent in men. Women have two X chromosomes. A mutation on one X chromosome gene may be compensated by a normal gene on the other. Studies suggest that there are actually two slightly different genes for green, so some women may have 4-color vision (tetrachromatic vision).

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[3] For the technically minded, the L peak is at 564nm, M is at 534nm, and S is at 420nm. The James Webb Space Telescope captures only infrared light. To get full color images, NASA remaps shorter IR light into the Blue range, medium IR light into the Green range and Long IR light into the Red range.

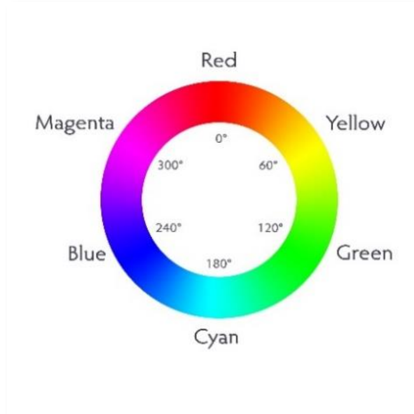
[4] The blue cones are also used to synchronize our internal circadian rhythms to the 24 hour day.

[5] The ganglion layer also plays a major role in the color constancy feature of human vision.

[6] The human visual system is complex; see this article in Wikipedia: Visual System.

The retinal pigments in animals can be quite different. Most mammals have only two retinal pigments; some have four. The mantis shrimp has twelve! Bird and insect vision can extend into the ultra-violet. We can only guess how other creatures see color. So, surprisingly, it's all about the biology! Light itself has no inherent color.

An artist thinks about the primary colors of light and wonders what happens when you mix colors together. Red and Green light can be mixed to make Yellow; Green and Blue mix to make Cyan. If you wrap the spectrum around on itself to form a wheel, a new color emerges in between Red and Blue, Magenta[7]. These mixed colors, Yellow, Cyan and Magenta, are called secondary colors.



The names of the six colors shown on the wheel are well established. If you start to work with colors that are in between these, the names can get pretty confusing. Some color wheels show a color name between Magenta and Red; it might be Rose, Plum, or Pink.

It's easier to be precise about these mixed colors as a position around the 360 degrees of the wheel. Red becomes 0° (or 360°), Green is 120° Blue is 240°. The secondary colors have values halfway in between. For example, Yellow is halfway between 0° and 120°, or 60°.

To be precise about this topic, 'Color' is a general term that includes all the names above. It also includes Black, White, and Gray. 'Hue' never includes Black, White, or Gray. A complete color wheel does have tone and tint values that include black and white. The wheel shown should really be called a Hue Wheel.

Reproducing Color

Theoretically, we can combine light of the three primary colors to produce full-color images on computers, TVs and other devices. On digital devices these colors have been produced by red, green, and blue light emitting diodes or phosphors[8]. But I often notice visiting that when appliance stores that TVs showing the same demo video have different color palettes. In fact, a given image may have a different palette on every device on which it is displayed. This is because the LEDs or phosphors are different. Your iPhone's red led will emit a different red wavelength than your laptop, or TV.

If you have printed this document, the colors have been produced by cyan, yellow, magenta, and black inks[9]. Different dyes or pigments produce different colors. The same ink set will produce different colors on different papers because the 'white value' in a print is the color of the paper itself.

Both displays and printers need to be color calibrated and profiled. Printers will require a profile for each paper and ink combination used. 'Calibration' is the key word here. If we want our computer displays and printers to produce images the same way we see them, we must know something about how each device

[7] The rainbow is the span from red to violet (RGBIV). But because it does not wrap into a circle, the rainbow does not have magenta, which requires a mix of red and blue. Magenta is thus a *non-spectral* color, as is white.

[8] If you are still not sure about this, use a small magnifying glass to take a close look at your TV screen, phone screen or computer monitor. You will see the red, green, and blue phosphors that make up pixels. If you do not have a magnifier, look through a pair of binoculars backward. (You have to get close.) Because we create colors by adding various amounts of red, green, and blue, this is an *additive model* of color.

[9] If you use an inkjet printer you may be able use a magnifier to see the micro dots use to spray the ink onto the paper. Red items will be produced by magenta (subtracts green) and yellow (subtracts blue) inks. This is a *subtractive model* of color.

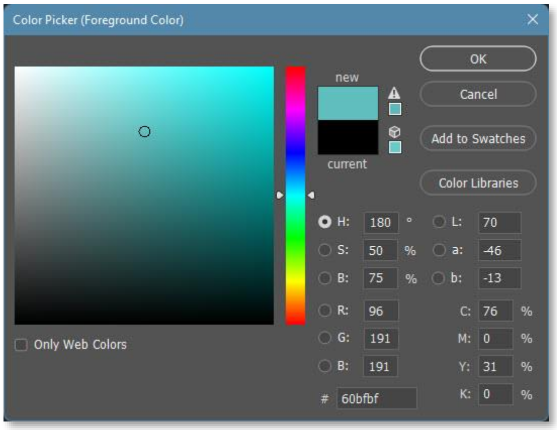
produces color. For example, what is the actual range of red colors in the red LED on your display? What is the range of color in the cyan ink of your Epson printer (vs your Canon printer)?

Calibration is the process of evaluating the actual wavelengths of color produced on a color device. With this information, calibration software produces a 'profile' that measures the differences between the device and a standard color model. We can then apply this profile that describes how to modify those colors so your print looks like the image on your display. This may be a slight change in the brightness of the red LED in a display pixel, or the amount of cyan ink in an inkjet's pico-droplet.

Models & Spaces & Gamuts, Oh My!

Colors in Photoshop, Lightroom, and Adobe Camera Raw, can be specified several ways. Since these software products work on computers, numerical models for color predominate.

Color models are a mathematical way to describe colors with numbers. The RGB color model uses three numbers to represent the three primary colors, based on the eye's red, green, and blue sensitivities. If we think about colors in terms of Hue, Saturation and Lightness, we are using an HSL representation of the RGB color model. Photoshop also supports the CMYK printing color model which uses four numbers for the four inks used in printing, cyan, magenta, yellow and black.



If you use Photoshop's Color Picker to select a foreground color, you will see this dialog. The small dot in the color swatch lets you select a precise color; the corresponding RGB, HSL and CYMK numeric values for these color models are displayed. You can click & drag the dot or change any of the numbers individually. Note that the 'radio button' in front of the letter H: is selected. If you are following this on your computer, be sure that H is selected.

This is Photoshop's default display, but you can look at other displays that emphasize specific aspects of the color model. Try clicking on the button in front of S: .

A Color Space is a defined representation of colors. The sRGB color space was designed for computer displays. Modern digital computer displays are virtually 100% compatible with the sRGB color space. AdobeRGB is a wider space suitable for high quality color printing. There are expensive computer displays that match the AdobeRGB color space. ProphotoRGB is a very wide color space. LR uses ProphotoRGB internally and does a color space conversion depending on output. Note that sRGB, AdobeRGB and ProphotoRGB are all based on the RGB numerical model.

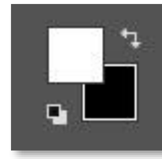
Gamut is a specific set of colors a device can produce. Different printer inks may produce different colors with the same three RGB values. Your image may contain AdobeRGB colors that your printer cannot produce. Photoshop can warn of these 'Out-of-Gamut' colors and offer a way to place them in-gamut.

All devices used in the creation of color images, cameras, displays, printers, scanners, etc., can be profiled to accurately reproduce color. Such color profiles are used extensively in PS, LR and ACR so what you see on screen will match what you see on a print. Missing or mismatched color profiles are a common source of color and tint issues.

It is worth repeating that the RGB, HSL and CMYK models are numeric. Complex mathematic formulas are used convert colors between these models. Hence these predominant in computer image processing. There are other color models, Pantone and Munsell for example, which are not based on a numeric model.

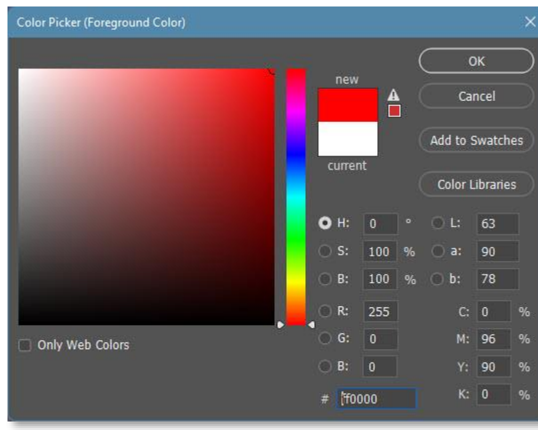
Solving the Color Problem

Let's look at the RGB and HSB numeric representations of the RGB model. Later, we'll look at the L*a*b* Space. You can use the Color Picker on the Photoshop toolbar to see RGB and HSB values for any selected color. Tap the D key, then the X key to make the foreground white, then click the foreground box.



RGB

This is the Photoshop Color Picker. What you are seeing here is a large box that is mostly red. Just to its right is the colorful 'Hue Strip'. The RGB model treats each primary color equally. On the color picker dialog, the RGB color values run from 0 to 255. A display uses three LEDs to produce each picture element (pixel). The three RGB numbers on the dialog form a triplet in R-G-B order for each pixel. The triplet shown, 255,0,0 is bright red. The triplet 255,255,255 is white, a mix of all three primaries at maximum value. The triplet 128,128,128 is the primaries at half their maximum value, or middle gray.



HSB/HSL[10]

The HSB model uses the hue angle shown on the color wheel to represent color. The H: value is 0°, which is the Red location on the color wheel. Both Saturation and Brightness are at 100%. If you are following this in Photoshop, be sure the button labelled H: is selected.

Try this:

- ✓ Moving the dot to the left is like *mixing with white*. Hue and Brightness are unchanged, only Saturation changes. The resulting pastels are called Tints.
- ✓ Moving the dot from top to bottom changes brightness, Hue and Saturation are unchanged. This is like *mixing with black*. These darker colors are called Tones.
- ✓ Use the Hue Strip slider to change hue. Watch the numbers. Keep ~~playing~~ experimenting.

If you play with the selection dot and the Hue Strip slider, you'll get a good feel for these systems. While the RGB and HSL use different numbers, they both can represent the same colors; black to white, Tints (pastels to saturated) and Tones (saturated to black). As we will see below, the numbers for a selected color also depend on the color space.

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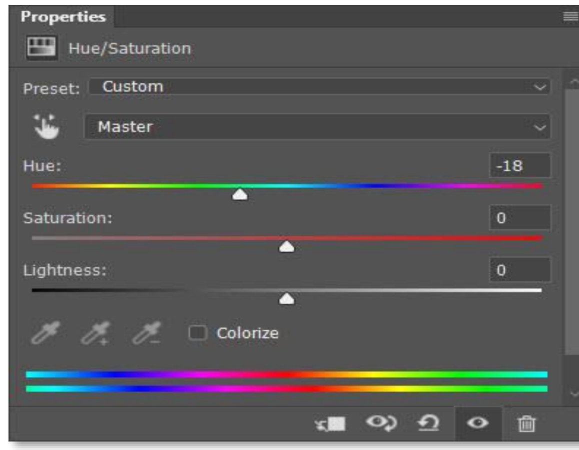
[10] Looking through a good number of references to HSL and HSB color models, it seems the terms Brightness, Luminance and Lightness are used rather loosely. Photoshop uses HSB in some dialogs and HSL in others. While there may be technical differences, they all produce a similar effect.

Note that In LR and ACR, sliders on the Color/HSL or Color Mixer panel show RGB values a scale of -100 to +100. This is somewhat confusing but provides a way to make changes to the 'current' values in the image when first opened.

Hue Rotations



Just for fun, open the included file *ColorWheel.tif.* From Camera Raw, click the Open button; in Lightroom, choose Edit in Photoshop.

Then, in Photoshop, open a Hue/Saturation adjustment layer. With 'Master' selected in the color drop-down, move the Hue slider. This will change the hue of all colors in the image. The whole color wheel appears to rotate! Hence, *hue rotations*!

In the Color Picker dialog above, Hue numeric values were 0° to 360°. In the Hue/Saturation adjustment layer the numeric values for Hue go from +180° to -180°, somewhat different but still the full 360° circle.

Close this file without saving changes.

Wetware (Human Vision) vs Hardware (Printers, Sensors & Displays)

The photosites in a digital camera, the dyes in color film, the RGB LEDs in digital displays and CMYK printer inks do not match the color sensitivities of the human eye. If they did, we could eliminate, or at least minimize, the color problem. One set of color values in a color-space would suffice to accurately reproduce any image on any display or device.

In real life, every camera sensor will respond differently to the colors of light, and every display will emit a slightly different tint, tone or hue of each of the three primary colors. Printer inks work with the CMYK color model and vary widely among printer manufacturers. For this reason, the RGB color-space is said to be device dependent. These devices must be *profiled* in order to produce accurate colors.

A *profile* provides a mathematical way to transform a given set of RGB values from one device into values that match colors on a different device. No hardware manufacturer can produce a profile that will accurately reproduce colors on their device to any other device. However, manufacturers can produce a profile for their device to convert to an international standard, the CIE model.

CIELAB - L*a*b*

The International Commission on Illumination (usually abbreviated CIE for its French name, *Commission internationale de l'éclairage*) is the authority on light, illumination, color, and color spaces. CIELAB was designed so that the same amount of numerical change in these values corresponds to roughly the same amount of visually *perceptible* change.

Converting RGB (and HSB) numeric values back and forth requires both mathematics and a knowledge of each color space. The CIELAB color model acts as like a connector between devices. An image captured on one device can be guided through the color processing 'pipeline' and displayed accurately on another device. Profiles provide information about the devices involved, so the CIELAB color space is 'device independent'.

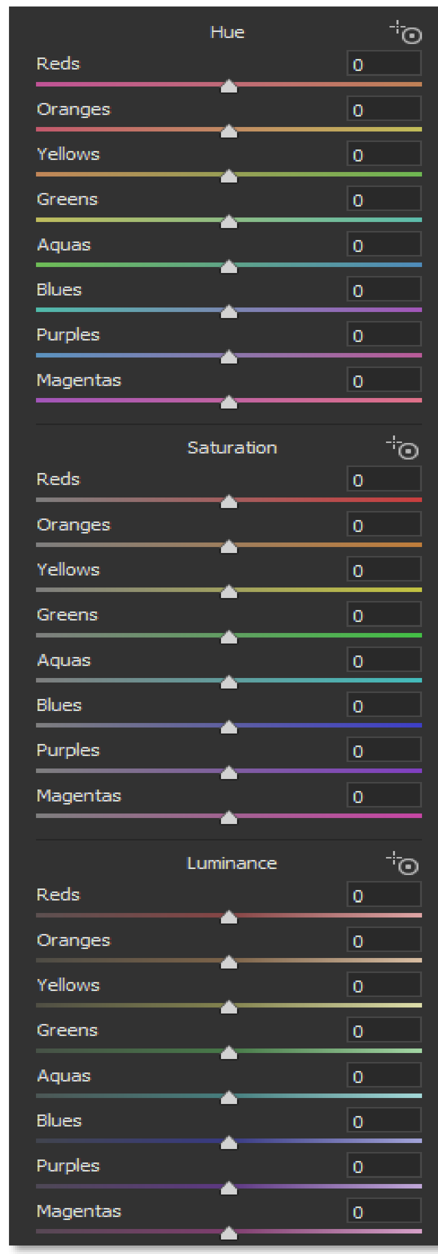
CIELAB is a color space. It uses L*, a*, and b* values to separate Lightness from color.

L* : Lightness from black (0) to white (100).
a* : A green-red color component from green (−) to red (+).
b* : A blue-yellow color component from blue (−) to yellow (+).

The Lab color space is designed to accurately match human vision as closely as possible. It was developed by asking humans to adjust the brightness of three standard illuminants (one each of R, G and B) to match defined color swatches. The * symbol indicates that these values are *perceptual*. (I'll drop the Asterix and use just Lab from here on.)

Lab color space color values (a & b) are closely tied to how our retina's pigments respond to light. Device independence and *faithfulness to human vision* are the key attributes of Lab.

Color Adjustments in LR & ACR



At right is the full Color Mixer of the ACR. In LR, the Edit module has a similar HSL/Color panel. The Color Mixer panel has multiple ways to target colors. Based on the labels, we'll call this HSL mode.

This is the full HSL panel. These can also be displayed individually. There is also a simpler version of the panel which just shows the eight colors to adjust. Note that the sliders represent the usual primary (RGB) and secondary (YCM) colors, plus orange (O) and violet (V). (Some color printers actually have orange and violet inks.)

Open the included file *ColorWheel.tif* in LR or ACR, then select the Color Mixer panel.

In this version, you can use the individual sliders, or click the +⊙ icon to launch a color picker that lets you select any color in the image to adjust. Use the color picker tool to click and drag left and right to make an adjustment. Here's what to look for: Move the sliders; watch the corresponding areas on the color wheel.

The effect of the adjustment you made is centered on the selected hue and tapers off to adjacent hues. The hue angles affected seem to be about 15° to each side. No other part of the color wheel is affected.

This is powerful! I use this frequently to make a slight hue adjustment to sky colors away from cyan toward blue. Small adjustments are quite smooth; large adjustments can produce banding and extreme color changes.

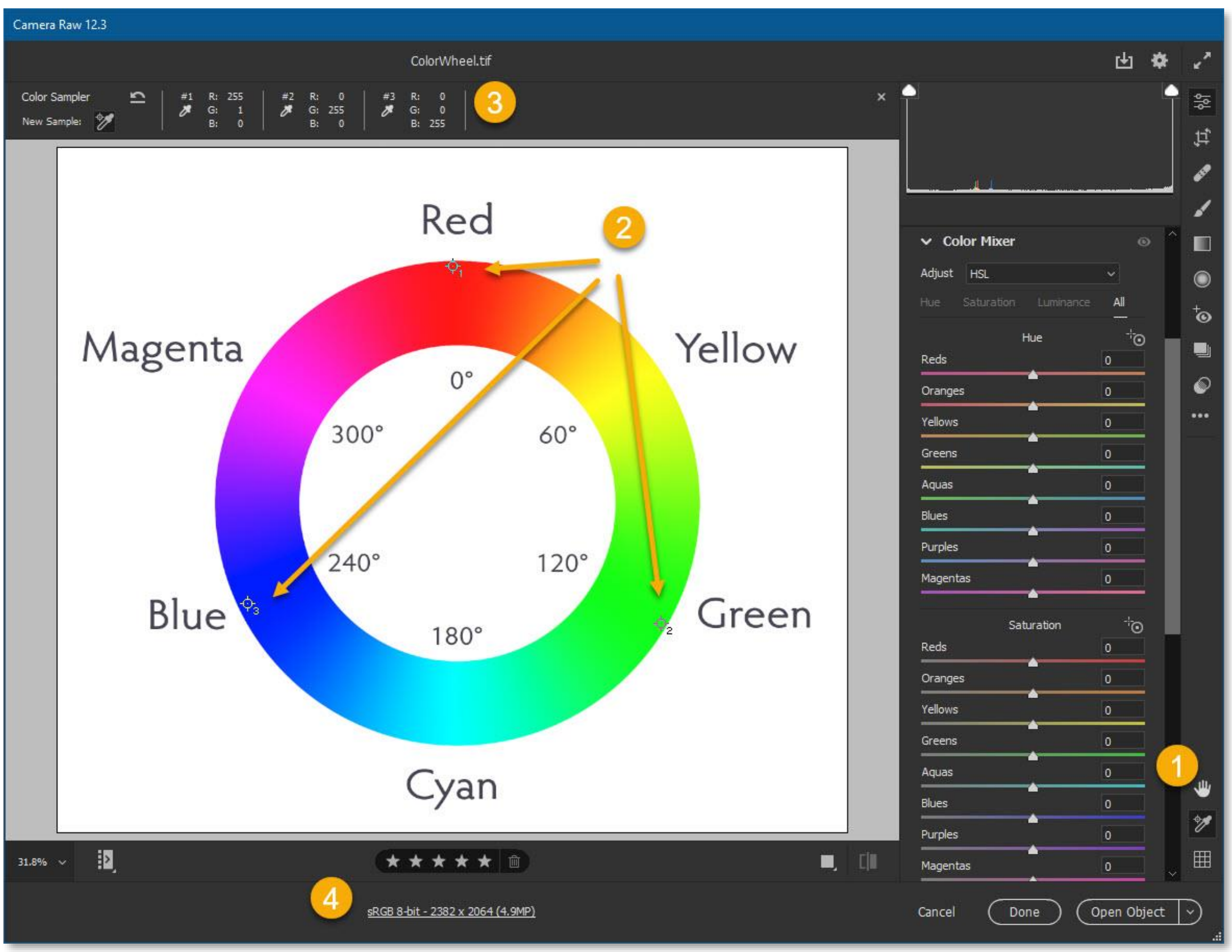
Close the file using the Cancel button so no changes are saved.

Looking closer

Below is a screen capture of Adobe Camera Raw where color samplers have been placed on the image. The RGB values are reported at a new ‘readout’ panel at the top of the screen. Sadly, I cannot find a way to save an image file with the sampler panel and sample points intact. It has to be created as needed. (I cannot find this feature in Lightroom. You can send the image to Photoshop and use the Camera Raw filter to follow along.)

Open the file *ColorWheel.tif* in ACR again, this time …

1. Click the Color Sampler tool at the lower right just below the Hand tool. The cursor changes to an eyedropper.
2. Click once at the top of the red segment of the color wheel, then green and blue segments.
3. This created the RGB ‘readouts’ panel at top for the three samplers. (You can have up to nine.)
4. Set the workspace to sRGB to match the color space of the image.



Work all the sliders. Watch the RGB values and how the color wheel colors change. Since red, green and blue are sampled here, you will see the biggest effects using the red, green and blue sliders. You can move existing sampler icon by positioning the eyedropper over it. When the cursor changes, click and drag. (If you make other adjustments, the regular cursor may appear. To get the eyedropper back, click the ‘New Sampler’ icon on the top ‘readout’ toolbar.)

Hidden gem: Right click on the histogram to change the sampler readouts from RGB to Lab!

Cancel out again so changes are not saved.

Tip: If you haven't noticed, as you move the cursor across the image, the RGB values under the cursor are reported at the top of the histogram. This can make it easier to find a specific location for your samplers.

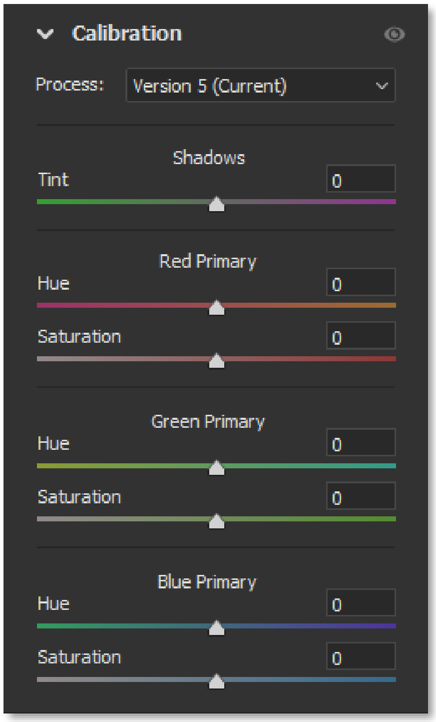
Most of your color adjustments in LR/ACR will be done using Color Mixing (HSL) panel, the Split Toning panel, or the newer Color Grading panel. In Photoshop, the Hue/Saturation, Selective Color and Color Balance panels are available for this.

Virtually ALL the color siders you will use in PS, LR or ACR target specific colors and treat the red, green, and blue primaries with equal 'weight'. Reds go from 0 to 100, Greens go from 0 to 100, and Blues go from 0 to 100. Even the Hue sliders which use degrees, treat the primaries equally.

This is exactly what the RGB model enables for photographers: R, G, and B are treated equally and adjustments can target specific hues and values very precisely! This is not true in the calibration panel as we will see next.

The Calibration Panel

Finally, we're prepared to look at the calibration panel! The screen capture at right shows the Calibration Panel. At the top, the Shadows slider applies a tint to shadows that can be adjusted between green to the left and magenta to the right. (A similar slider is part of the Basic editing panel in LR/ACR.) This slider allows you to remove the magenta cast found in some under-exposed images by moving the slider toward green. I find this slider quite interesting. Green and magenta are complementary colors. In the Lab model, the 'a' slider would be yellow-blue, the 'b' slider would be red-green. This adds a slider between green and magenta; magenta being a non-spectral color.

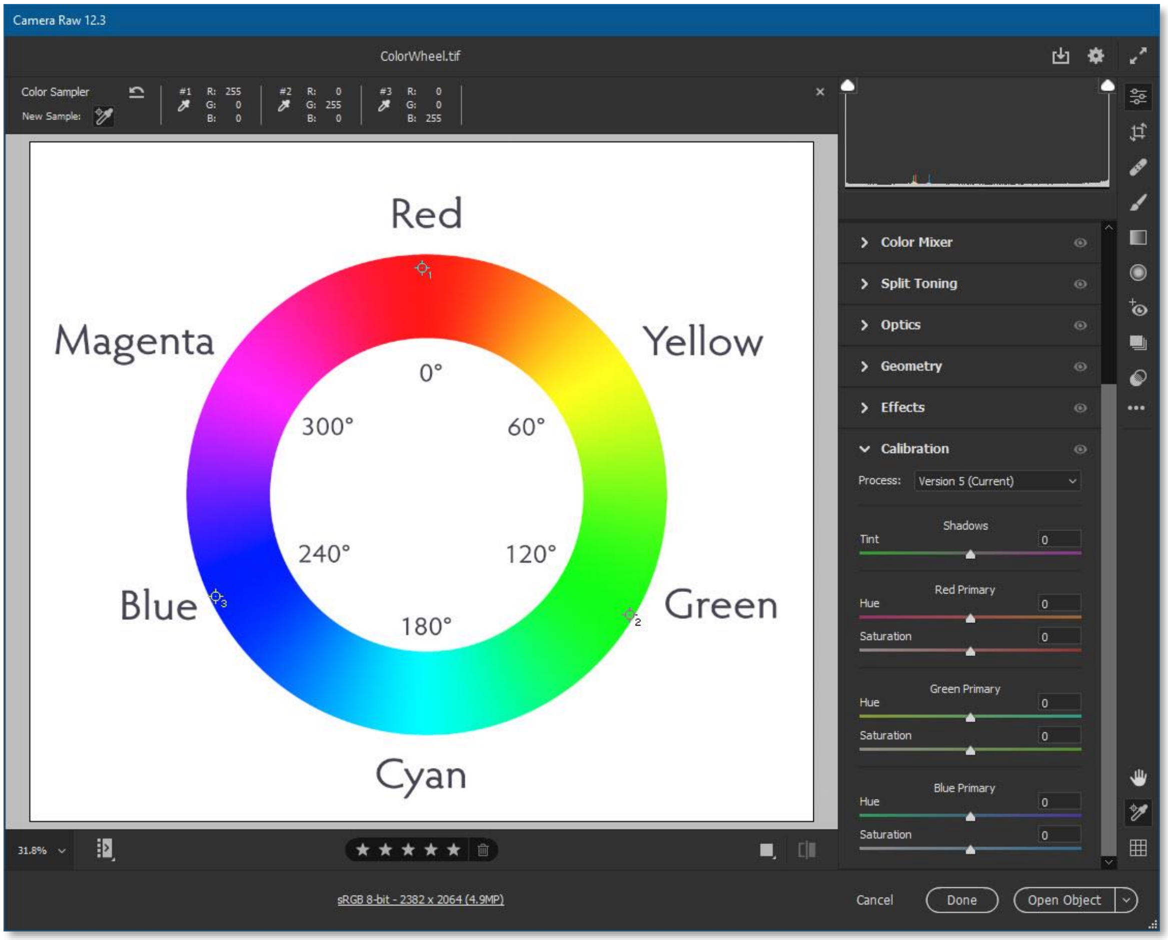


Below that are Hue and Saturation sliders for the three primary colors of light, Red, Green and Blue. They look just like the sliders in the Color Mix panel. But they do not work the same way.

Let's try and figure this out!

Open the color wheel file again. On the next page is the same screen capture of ACR with color samplers applied to the three primary colors. I omitted the arrows and scrolled the tools panel to show the Calibration panel.

Note that all show a value of 255 in their primary color and 0 for the other RGB triplets.



Here are some things to look for:

1. Start by moving the red Hue slider, watch the RGB values for sampler #1. The R value changes only slightly, if at all, but the G and B values do. You can see a shift in the colors around red. This same pattern follows for Sampler #2 for green and Sample #3 for blue. The G and B values remain almost constant, respectively, while the other values in the triplet change.
2. Go to the Basic panel and reduce Saturation or Vibrance. Your colors will look like pastels. Repeat the hue slider step above. You will see some changes in the RGB values for each primary, but, as above the R value for the red hue change will be minimal. (The ZIP file has a pastel color wheel if you wish to use that.)
3. With the pastel version open, run through each of the saturation sliders. All produce noticeable increases in their corresponding primary colors. But look closely when you increase blue saturation. There will be a very noticeable increase in saturation for the red and yellow segments. This is the surprise effect of the Blue Saturation slider. This is the Secret Slider! (More on this below.)
4. Reset all the changes you've made so the full color version is back. (Hold down the Alt/Option key to reset each panel.) The red sampler's R value should be back to 255. Now use the workflow options (location 4 on page 5) to first set the color space to Adobe RGB. R:255 will have changed to R:219. Now change this to ProPhotoRGB. The R: value will change to R:179.

Findings

Hue changes in the Color Mixer panel work very differently than the hue sliders in the Calibration panel. If you read through the Adobe documents for LR and ACR, the Calibration Panel is intended to facilitate creating camera profiles to match colors across different camera brands and models. If you do calibrate multiple cameras this way, LR/ACR allow you to set a default profile for each camera that will be applied automatically.

The Hue and Saturation sliders in the Calibration panel use the CIELAB color space. The sliders affect colors around the whole color wheel. This makes targeting specific hues and values in an image very difficult. But they are enormously useful to make image-wide shifts in Hue and Saturation!

There is one other place in LR/ACR where the CIELAB color space is used. If you choose B&W on the Basic panel, LR/ACR will apply the Adobe Monochrome profile to your image. This will result in yellows and greens appearing near white, while blues and reds will be darker. This matches the peak sensitivity of the retina to the yellow-green portion of the spectrum.

The Secret Slider

In step 3, we noticed the effect of the Secret Slider, the blue saturation slider. The calibration panel uses the CIELAB color space to approximate human vision. *Increases in blue saturation have to be accompanied by corresponding increases in red and green saturation.* The human eye sensitivity curves shown on page 2 show significant red and green sensitivity in the blue cones. The Blue Saturation slider adds warmth to an image because adding both red and green is the same as adding yellow! This is the basis of the 'Secret Slider' effect.

Here's the deeper secret of this slider. Photographers who promote this technique use it for images with few blue tones or none. The common examples are studio portraits, where it produces a really nice glow to skin, and tightly cropped sand dune landscapes where even light tan dunes develop a warm tone. Blue tones in an image can get un-naturally saturated, so some photographers use the Secret Slider, then reduce blue saturation in one of the other color panels.

Color Models

In step 4, changes in the color spaces in the Workflow dialog (sRGB, AdobeRGB and ProphotoRGB) changed the RGB values even though the on-screen colors did *not* change! RGB model values are just numbers. They must be interpreted according to the selected color space, using color profiles. The colors shown do not change, but the number do. R:255 is a saturated red in the small sRGB color space. It is R:219 in the larger AdobeRGB color space, and R:179 in the much larger ProPhoto RGB color space. The color did not change, only the number value of its place in the different color spaces.

Conclusion

The Calibration Panel works differently than the RGB color model in ACR's Color Mixer or LR's identical HSL/Color panels. It uses the CIELAB color model based on actual human color perception.

- ✓ It is best to apply Calibration changes early in image processing; changes made in this panel affect the entire color wheel so you will find changes in all colors in your image. For this reason, many photographers move the Calibration Panel in LR/ACR to just under the Basic Panel. [11]

[11] Blake Rudis of the f/64 Academy recommends this in his YouTube channel: HIDDEN Raw Workflow

- ✓ Adjust specific hues and tones *after* using the Calibration Panel. In fact, changing brightness and contrast to the whole image or just selected areas can change tint and tone. Color mixing and color grading are best done last. Move these panels to the bottom of the module stack.

To change the visibility and position of Panels in the stack, do the following:

ACR: Right click on any empty space on the right side of ACR, or any panel title. Choose the 'Edit Panels to Show' option.

LR: Select the Develop module, then right click on an empty space or panel title. Choose the 'Customize the Develop Panel'.

For most photographers, the key device profiles are those for the computer display and the printer/paper combination. Calibrating cameras may be appropriate for studio work under consistent lighting, but the usual 'to taste' adjustments to images - hue, saturation, brightness, contrast - impact an image far more than matching camera profiles.

Finally, getting, installing and creating device profiles is a big subject. Keep checking back to my website for future updates.

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Reference: "Vision and Art : The Biology of Seeing", Margaret Livingstone, ISBN-13 : 978-1419706929.

Super Geek : Sometimes Biology and Physics come together in astonishing ways. The relationships of primary (RGB) and secondary (CMY) color models in photography are echoed in the 'color' attribute of quarks and antiquarks. This puts the 'chromo' in quantum chromodynamics. Check out this video by Matt O'Dowd on YouTube's PBS Space Time channel : Why Isn't the Nucleus Ripped Apart? The color theory starts at about 9 minutes. My favorite model is not Eleanor Gow or RGB, it's SU(3).