Color Control of LED Lights

Why it is not as easy as you might think.

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A Bit about Additive Color Mixing

With recent mass acceptance of solid-state LED lighting, it's time for an explanation of this technology's capabilities, complexities and ways in which it can be tamed. LED lights use multiple sources to achieve different colors and intensities. Additive color mixing is nothing new to our industry. We've done it for years on cycloramas with two or three gelled cyc lights hitting the same surface. The first 'intelligent' light that I used which incorporated additive color mixing was a spotlight that had three MR16 lamps, each fitted with dichroic glass, one for each of red, green and blue. In the early days, the DMX protocol for lights such as these was simply three control channels. Using early moving light desks, the drawback of just three channels was that these lights had no intensity control. For instance, if you had a mixed rig of LEDs and moving lights, when you pulled down the Grand Master, the LEDs would stay on. It also meant that you could not roll down the brightness even if you liked the color. Typically, moving light programmers would also build a "Color Black" so they could easily turn off these lights.

Control and Definition of Color

With the advent of abstract control (marketed as Natural Language Control with Cognito), we gave additive lights a virtual intensity control. So, even if the manufacturer defined the light to use three DMX channels, Cognito allocates four "handles" to control it: Intensity and three color parameters. Note, I said three color parameters rather than Red, Green and Blue. That is because RGB is just one way to describe a color; it is one of the Color-Spaces. Another way to describe what comes out of the light is Hue, Saturation and Luminance (some say Intensity or Lightness instead of Luminance). Equally valid is Hue, Saturation and Value. Value is sometimes referred to as Brightness and is similar to HSL, and in particular, Hue uses the same units. On the other hand Saturation in HSL and HSV differ dramatically. For simplicity, I define Hue as Color and Saturation as the amount of color (vs. lack of color definition). I also try to remember if 'L' is set to 100%, that is white, 0% is black and 50% is pure color when Saturation is 100%. As for V, 0% is black and 100% is pure color and the saturation value has to make up the difference. That over simplifies it, but let's carry on, as we're not done yet.

Another valid description of what comes out of a light can be described in the triplet CMY (Cyan, Magenta, Yellow). Those are the primaries used with subtractive color mixing. If you start with white light and you desire red, what you do is introduce two filters; one is Magenta (which removes the Green component of the white light) and one is Yellow (which removes the Blue component of the white light).

With Cognito, when controlling LEDs, you have the choice of adjusting Intensity and one of either RGB, CMY, HSL or HSV. There are some variations on these themes to come, but for now, lets move on.

Mixing Color with LEDs

For most of us our eyes can detect light in the range of 390 to 700 nanometers. The first LED luminaires used just three color dies. Those were Red (about 630 nm), Green (about 540 nm) and Blue (about 470 nm). It should be no surprise to you (contrary to what your grade school art teacher said) that mixing those three colors does not create every color your eye can see. Below is a hypothetical locus of a three-color RGB system rendered on, what we will call, the entire visible light spectrum.

Note the “triangle’s” vertices hover around deep saturated Reds, Greens and Blues. Altering the power supplied to each die ‘should’ allow you to reach any color inside of the locus. I quote ‘should’ because, after all, this is all theoretical and many factors affect what really happens. Foremost, the exact location (or wavelength) of the R, G and B can vary drastically from light to light. This is similar to how ‘standard’ colored glass varies from batch to batch. In the manufacturing world we call the process of qualifying the parts ‘binning’ and it describes the tolerance a factory may accept before installing the LEDs in a fixture. Also the control systems (the pulse width modulation rates and power supplies that control the dies) may introduce artifacts seen in sub-second time slices, so how you view the image, either by camera or by naked eye, can affect what you see. Even moving your head quickly can emphasize some of these artifacts. Finally, who is to say that this hypothetical gamut is representative of the real world? You are likely viewing this document on a computer screen that only uses RGB emitters to render the images in any case.
Given all the caveats above, the gamut and locus shown can just about describe Hue, but not Intensity nor Saturation. If you do a quick Google Search on ‘color gamut’ you will see circles, donuts, cubes, cones and even fruit, all attempting to show the three-dimensional relationships of HSL etc.

Adding more colors at the source

As LED technology evolved, prices dropped and various intellectual property lawsuits subsided allowing more companies to enter the market. Lighting designers' appetites for this new light source grew and along with that came demand for brighter lights and more consistent color control. To answer that call, binning became tighter and the number of sources increased. New LED colors became available too; colors such as White, Amber, Cyan and Violet. Initially, the most popular integration was the RGBA, where manufactures added an Amber chip onto the light. This made the locus that was sort of triangular look more like a rectangle (or at least a four-sided-ish thing).

The addition of Amber offered slightly more colors, but not necessarily more light. Brightness is purely a matter of efficacy and the number of watts you pump into the luminaire. If you want a brighter light, just add more or bigger LEDs.

Another variation on this theme (just to confuse the brightness vs. color debate) was the RGBW. The White LED grossly overlaps colors you could already reach by adding primaries together. So in this case, Whiter does mean Brighter. Lights exist that use both White and Amber with the three other colors (RGBAW). Drawing the effect of white light without fully describing Brightness is a little difficult and beyond the scope of this essay, so please excuse the lack of an image on this topic.

What to do with all these LEDs

This is becoming a lot more complex than turning a light on and off. Luckily, Cognito's Natural Language Control allows you to drive any type of color system discussed so far (additive RGB, RGBA, RGBW, RGBAW, and subtractive CMY) in very simplistic ways. Cognito has a general color picker, a series of popular gel colors and simple three-slider mixer. If you use the advanced wheel modes to mix color with Cognito, apart from Intensity you are offered three distinct color parameters. For the sake of repetition, those are RGB, CMY, HSL and HSV.

As LED technology continued to advance, chip manufactures managed to make Orange, Cyan and Violet LEDs too. These have been used in “seven-color” system (Red, Green, Blue, Amber, Orange, Cyan and Purple). This again distorts and widens the locus giving us potentially more colors.

Unfortunately, Cognito has not implemented an automatic method to control the orange, cyan and purple chips. The issue is, for any one color (at varying brightness) there are multiple combinations of power to each chip that can get you to that one point in space. Lucky for us, those who manufacture the seven-color systems have figured out the ‘best’ way to get the ‘brightest’ color light and it’s important to note that only the light manufacturer can provide this solution properly. They present this to you using one of two systems that we all know and love: RGB or HSL. The definition of what RGB brings you is theoretical and is unique to their lights in their implementation. Likewise, an implementation of HSL is yet another way of getting to the same end point. When comparing RGB to HSL control, one is not better or different or faster than the other. On a properly designed fixture, each can achieve the exact number of colors as the other.

A closer look at color spaces

If you accept that there are different ways to represent color, it’s easy to accept that the units defining it can be arbitrary too. Lots of lighting consoles represent things in percentages. Cognito even represents Hue as a percentage, though some may argue that it would better be represented in degrees measuring a position on some arbitrary color wheel. If you were to define the wheel, where would you put, for instance, red? At zero degrees? Maybe the units should be in radians. Where is zero in any case? At 12:00? At 6:00? What lies to the right of zero? Amber or Pink?

Using a real-world example, let's examine the possibilities. Say we're doing a musical and we're lighting the cyc with color mixing lights. We're doing a sunset scene and the designer wants a transition from amber to pink. Using the RGB color space, Cue 1 is Amber (R=100% G=60%, B=0%) and Cue 2 is Pink (R=100% G=0%, B=60%)

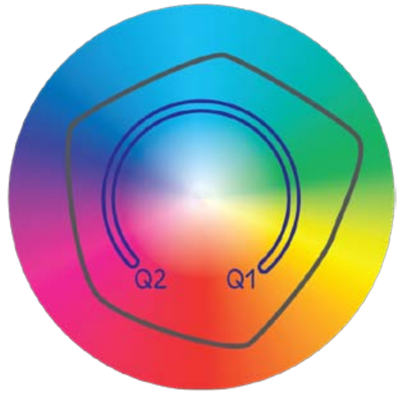
On any lighting console that defines color as RGB the transition you see above is exactly what you get. It is a straight line from Amber to Pink going through a slightly less vivid color of red. I say 'slightly less vivid' because in this case, the distance from the center of the wheel represents the saturation of the color and the mid-point on the line between the two end-points is closer to the center of the circle, if only slightly in this example. But imagine a transition from Pink to Green. In this model, moving in a straight line takes you right through white. This may or may not be desirable.

If your lighting control system is as capable as Cognito, you may describe the two cues slightly differently. In the example below, the two end points are the exact same: Amber and Pink. But in this case, the colors are represented using HSL. Cue 1 is Amber with a Hue of 10% (percent being a rather arbitrary unit for hue) and Cue 2 is Pink with a Hue of 90%. Note that if you go counter-clockwise from amber, you reach red.

The transition is from Amber to Pink and in this case you pass through a Red that has the same saturation as the two end points as it is equidistant from the center of the circle. We move in an arc, not a straight line.

But what if the color space was defined differently? Say it was mirrored so that when you were on Amber and you moved counter-clockwise on the wheel you would first reach Yellow instead of Red. In fact, you'd have to go a long way before you reached Red. Below, Cue 1 is again in

Amber (Hue' of 10%) and Cue 2 is Pink (Hue' of 90%). Those are the same values, they just appear at a different place in space.



This sunset sequence might be something you see on another planet, but likely not in your average musical. Cognito anticipates this conundrum and offers you yet MORE ways to define color in an attempt to ward off alien sunsets. As these are purely hypothetical color spaces (and we're running out of letters), we've dubbed these the as the 'primed' version of HSL and HSV. If you read carefully above, you will see that Amber was defined having a Hue' of 10%. For this functionality, we defined our own color spaces HSL' and hsv'. The ' after the triplet defines the mirror image of the 'normal' color wheel emphasizing that what happens when you go clockwise is different than what happens when you go counter-clockwise around the wheel.

Controlling the color chips in the light or at the console

As mentioned above, regardless of your light's primary color system (RGB, RGBA, RGBW, RGBAW, CMY or even the very odd and very rare two-string scrollers utilizing Cyan-White-Magenta:Magenta-White-Yellow), Cognito can write cues and do transition in multiple color spaces (RGB, CMY, HSL, HSL', hsv, hsv'). What Cognito cannot do at this time is use the six color spaces (RGB, CMY, HSL, HSL', hsv, hsv') to control a seven-color LED systems (RGBAOCP) because, again, only the light manufacturer knows the best way to control those seven LEDs to obtain a certain color. Luckily the light manufacturers have devised a method that uses just three control channels. But, to add to the confusion, some give you two choices: RGB and HSL. However, since HSL control of the DMX channels for a light are not standardized, Cognito can use only the RGB model to control the light. This is not a detriment because:

- Using the light's native RGB protocol you can reach ANY color using all seven chips.
- Whichever color the light produces for a given set of values of RGB, you can rest assured it is as bright as they can possibly make it.
- Using Cognito's Natural Language Control, you can still define colors and write cues in six color spaces (RGB, CMY, HSL, HSL', hsv, hsv').
- If you used the native HSL mode, you would very likely see alien sunsets and there is nothing you can do about it once you've hung the lights and started cueing.

OK, have you got all that? Breathe deeply because there are some more topics which need discussion and they have no bearing whatsoever on anything discussed above.

Making LEDs look like normal lights

Another attribute some of these modern day LED lights offer is amber-drift or red-shift. When a tungsten light cools (approaching off), it becomes more red, just like 2800K appears more red than 5600K. In practice, we choose colors assuming the light is at full, but we don't often drive lights at full in the theater, therefore we don't often see 3200K on stage. It's more like 2800K and as we approach a blackout, things do in fact get quite red. Even if you're using bluish gels, you can see this effect.

To help integrate theatrical LED lights into conventional rigs, manufacturers favor the red chip at the bottom end. This profiling makes the colors at very low light levels of conventional lights and solid-state lights match more closely. As a note, this intelligence is in the light and at this time Cognito does not artificially emulate a red-shift when fading to black.

Resolution

Solid-state response time is instantaneous, so if you stop driving the chips, they just stop making light. This is problematic when dimming LEDs, as slow fades using low-resolution control, particularly at low levels, ends up looking very choppy. Early-day LED lights did nothing to compensate for low-resolution control, but more recently, advanced LED drivers have added 'shock absorbers' in their firmware to smooth out the bumps.

The DMX protocol we use to control almost everything lighting in the theatre pushes out 8-bit data slots, or 256 different values in each control channel. For dimming a tungsten load, which inherently has thermal inertia, that is plenty enough resolution, but to pan a light, 256 steps over 360 degrees (or more) is far too few. Using two data slots gives you 65,535 different values and that is often enough. Cognito, by the way, can set and fade attributes with a precession of 1 in 4,294,967,296.

Using 16-bit control (two data slots together) is another way light manufacturers have solved the issue of choppy fades without having to add software shock absorbers. This puts the onus on the control desk to push lots of data, versus having to over-sample the data at the light and predict where the level is going. Doing this prediction can drastically delay the response time you get out of the LED lights which is a bad thing when you're trying to bump them in time to the music.

Curves

Another topic worth mentioning as some LED light manufacturers have incorporated it in their firmware is intensity curves. Dimmer manufacturers have often allowed you to tweak the curves that translate the incoming control level to the actual power output of the dimmer. Common curves are Linear, Inverted and Square-law. LED's instantaneous response time can be used with great effect when you want a quick strobe, but it can look unnatural when you have a mixed rig and you hit the blackout button. The LEDs go off in a split second, but the conventional lights take almost a full second to cool off substantially enough that no perceived light hits the stage. Some manufacturers offer various curves on the LED lights such as Quick, Standard, Linear and Tungsten emulation modes. Again, at this point in time, Cognito has no ‘control’ options to emulate Tungsten-type curves which essentially translate to a slower response time to the LED drive system.

Calibration

When you are using 20 LED lights to wash a cyc, variations in manufacturing dates and/or factory binning can easily be seen. For this reason, high-end solid-state lights have built in calibration channels. These channels allow you to dampen or boost the control level going to each chip. You can achieve the same results by tweaking up your color palettes for each light, but the thought is, if one light is consistently redder than the rest, you can pull down the red at a global level and hope things fall in line. I’ve found over the years, if you have a picky designer (and more power to them, that is their job), if they don’t like the cue they see with their eyes, you have to keep tweaking it until they do. It is useless to argue saying it ‘should’ be right because the desk said so. The designer always has the final say.

Correlated Color Temperature

The International Commission on Illumination describes Correlated Color Temperature as “*the temperature of the Planckian radiator whose perceived color most closely resembles that of a given stimulus at the same brightness and under specified viewing conditions*.” I am not a lighting scientist, so I describe it as *the color of white*.

Correlated Color Temperature is typically quantified in Kelvin. (Soapbox moment: Kelvin is a unit of temperature. The two units of measurement for temperature we are most familiar are Celsius and Fahrenheit. Both use degrees as placement on a scale. Kelvin is an absolute unit and as such does not. So don’t let me catch you saying “degrees Kelvin”.) To give you an idea of what the different values of Kelvin might represent when describing white light a candle is about 1800K, a domestic light bulb is about 2800K, a theatrical spotlight is 3200K, daylight is 5600K and TV screens can be upward of 10,000K.

Can intelligent lights with tunable color (blood red, bastard amber, no-color pink, pea green) define white too? Sure they can, but it can be difficult given there are so many flavors of white. For that reason, Cognito allocates another parameter when dealing with color mixing lights called CCT. For any light, whether you choose to control it in RGB, HSL or hsv’, you can also dial in a white in Kelvin. If you want pure red, the definition of white is rather meaningless, so we ignore it, but as you approach white Cognito interjects and drives the chips in a way that achieves the particular version of white you defined. To simplify it, in a three-color LED fixture, white might use all chips at full power, but likewise, white at a different CCT may drive the red chip a little harder than the blue and the green chips.

The two images below show the full color spectrum, but the middle of the circles show two different versions of white, one at CCT 3200K and the other at CCT 6000K.

This functionality is offered on may LED lights in Cognito's library and some lights offer similar functionality by setting aside a dedicated control channel mapping 0-100% to some Kelvin range the light can hit. For those that offer it natively, Cognito just outputs the value as published by the manufacturer and leaves the profiles of the other chips alone.

Conclusion

As you can tell, turning on an LED light is not as simple as switching on the reading light by your bed. If you take all the methods of control discussed here and do the permutations and combination, it's likely there are well over one hundred different methods of getting any one particular color out of an LED light. Cognito goes a long way to simplifying some of these tasks, but getting what you want on stage can be a daunting task if you don't take the time to understand what the console and lights do and how they interact with each other. Choose the system that helps you realize what you see in your head and let it help you get it on stage easily and quickly so others can appreciate it too.