***Joseph and the Amazing Technicolor Dreamcoat*, based on the story of Joseph in *Genesis*, is a family-friendly musical, but it's a challenge for a lighting designer trying to paint the stage with color, while coordinating with other costume and scenic designers to create a vivid stage appearance.**

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Spectral power distribution

BY **JAVID BUTLER**

In the Winter *Protocol*, we went into some of the basic challenges around controlling color. As mentioned in that article, it is very easy to go down a rabbit hole of mathematics to fully describe color. The depths of that rabbit hole are mostly of interest to color scientists, but it is worth taking a peek down there to understand more about how to control color in our daily work. This issue, we'll look more at the differences between direct emitter control and chromaticity control while keeping things at a high level. That means a certain amount of imprecision that I hope my friends on the TSP Photometrics Working Group will forgive. There is a lot of room between the level of precision needed in a lab and that needed in general use, however it is useful to understand the principles.

It's worth discussing the way LEDs produce light again, because it is so different from any other light source we commonly encounter. LEDs produce light through the recombination of electrons and holes in a semiconductor junction, and when an electron falls into a hole it releases a photon. The physics of this process is very interesting, but perhaps too much for an article that promised to only peek down the rabbit hole. Based on the materials used to make the LED chip, the energy of the emitted photons, and therefore the frequency of the emitted light, is very specific. That makes the spectrum of light emitted from an LED very narrow. White LEDs use an additional phosphor coating to convert a narrow blue or ultraviolet spectrum into a broader spectrum.

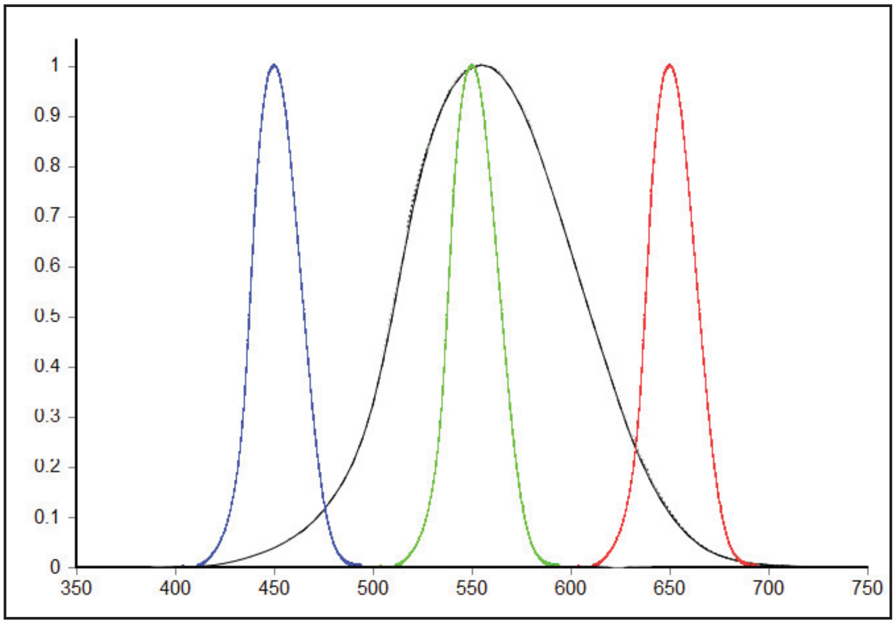
There are many ways to describe color, but they all come down to the energy of photons, and the energy of an individual photon is related to its wavelength. Longer wavelength photons are lower energy and we perceive them as red colors. Shorter wavelength photons are higher energy and we perceive them as blue. This is within the range of human vision, which is a very small part of the electromagnetic spectrum overall. Within that range our eyes are most sensitive to photons in the middle of the range, which we perceive as green. Taking the power (e.g., in milliwatts) of all the photons at each wavelength and plotting them on a graph, we get the spectral power distribution (SPD) of the light being measured. In general the range of human vision is considered to be 400 nm to 700 nm, though sometimes a wider range is used. Wavelengths longer than 700 nm are considered infrared, or heat, so sometimes a spectral power distribution will go to 800 nm or farther to show the heat produced as well as the visual spectrum.

Sunlight has a broad spectral power distribution that is also fairly smooth, although water in the atmosphere absorbs some frequencies, and our eyes evolved sensitivity to the spectrum of sunlight as filtered through the tree canopy on the African savannas. Fire has a spectrum that is different than sunlight, but is also relatively smooth. Incandescent lamps also have a smooth spectrum. Most discharge lamps have multiple sharp peaks in their spectrum, but they are designed to be perceived by our eyes as a white light through selection of the number of spectral peaks and where they fall in the visible range. Low-pressure sodium lamps, such as those used in streetlights, have a narrow emission spectrum similar to LEDs. Overall though, LEDs are unusual in our perception of light and color due to their very narrow spectral power distribution.

LED lighting gets complex because our eyes do not detect photons at all energies equally. It takes less energy from green photons, around 550 nm, to stimulate our color photoreceptors than blue photons at 450 nm or red photons at 650 nm. While spectral power distribution tells us a lot about the emission of an LED, it doesn't by itself tell us much about the color we humans will perceive. The luminosity efficiency function V(λ) shows us the color perception of our eyes at different frequencies, and combining that with the spectral power distribution of individual LEDs starts to give an idea of what colors we will see.

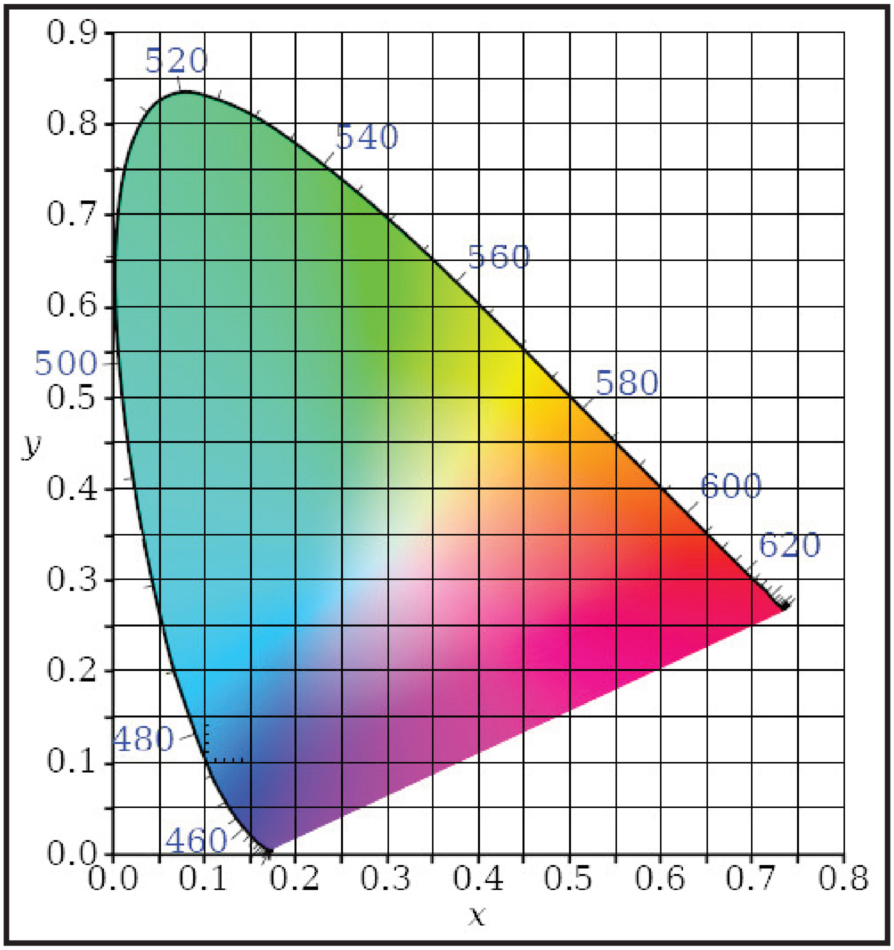
So far we have been discussing the SPD of light sources, but we generally don't look directly at sources and most of our world does not consist of matte white surfaces. Reflected color then is where the challenge starts. Historically used light sources, such as sunlight and fire, have broad spectrums with a wide range of frequencies. The SPDs of these sources have a very smooth curve and materials with very saturated colors will appear fairly consistent. Under LED lighting, though, materials can appear very different than under broad spectrum sources. In particular, materials that have a variety of saturated colors can be difficult to light. Some colors will be vibrant while others appear dull. A related problem is that colors can appear to change as they move from one LED fixture to another, say as an actor moves across the stage. Under incandescent light Joseph's Technicolor coat wasn't difficult to light consistently. With LED that changes. Let's look at why.

Colors must be in the source to see them in the light reflected from a material. That is the fundamental point to remember with LED lighting, so I'll repeat it. Colors must be in the source to see them in the light reflected from a material. If the source is low in green then reflected greens will not appear vibrant. If it is low in blue, even the most electric blue material will appear dull. And as Joseph strides across the stage from being lit with one set of fixtures to another the colors on the coat will appear to move. When done intentionally that might be a nice effect, but if it is coincidental then let's hope the actor playing Joseph sings well enough that no one notices.



Nominal 450 nm blue, 550 nm green, and 650 nm red LEDs plotted against the color response (cones) in the human eye. A green LED emitting the same power as a red or blue LED will appear brighter due to the increased sensitivity in that range. Additionally, small changes in the red or blue frequency can affect color perception. If LEDs in a fixture are not well matched to the reflected colors in sets and costumes, the scene could appear dull.

So you are getting ready to design *Joseph and the Amazing Technicolor Dreamcoat*, or any other show with saturated colors in costumes or scenery—which is pretty much every show other than *Our Town*. Lighting has a different role in *Our Town*, it has to tell the story of several billion years of history happening around the characters. Not kidding, read the foreword to the play. Anyway, as you start to select fixtures for the show you are lighting, take a look at the colors the scenic and costume designers are



Solid lines show increments of 0.5 for x and y chromaticity coordinates. Note how color changes are larger or smaller in different parts of the diagram. Tick marks in the lower left show 0.1 increments in the blue range, showing how small changes in chromaticity coordinates can produce noticeable color changes.

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planning to use, and compare them to the SPDs of the LED fixtures you plan to use. If you don't have the SPDs of the emitters, ask the manufacturers. Most of the time they will have them from when they developed the fixture. Look at the peaks in the emitters and where they fall compared to the colors in the sets and costumes, especially the blues and greens. While the luminosity function falls off in both the red and blue ends of the spectrum, amber or white LEDs in the fixtures can help a lot with the reds. Differences in blues can be very noticeable, especially if the material has textures or patterning of different blues. Greens can also be tricky, and newer fixtures include a "lime" or a "mint" emitter. These are often a greenish phosphor converted LED, and by themselves they are kind of a sickly green color, but mix them with some red or amber, and a little blue, and watch the magic happen. If the costumes or scenery have a lot of shades of green it will help to use fixtures with mint or lime emitters. These are things you can check before even setting foot in the theatre, and share any concerns with the rest of the design team.

Once you have access to the stage and fixtures, it's good to check the materials under the lights. I start with one emitter, the one closest to the main color of the material, then bring in the other emitters one at a time to see how the colors appear. After that I test different mixes to get a feel for how the material will appear under different lighting. In my current work, I'm more often doing this with carpets than costumes, but the principle is the same. It's not practical to do this with every color used, but will help with critical elements. If you find a color that is not working well, it's better to know that before staging is built and costumes sewn, so the team can work together to find an answer.

Some of you are thinking that you don't need to worry about that, your fixtures and controls have chromaticity control so you can select any color you want through chromaticity coordinates during dress rehearsal. I'm not going to argue with you, feel free to dash off for a drink while the rest of us keep going. Chromaticity control can get you close, but depending on the fixtures, communication protocol, and console capabilities, it may not give you everything you need.

There are many different color systems, and I promised to just peek down the rabbit hole, not jump in with both feet. So we'll use the *CIE1931* chromaticity diagram that most people are familiar with or have at least seen. Colors near the edge of the *CIE1931* chromaticity diagram are pure colors, theoretically a single wavelength. LEDs produce a narrow range of wavelengths, but generally not a single wavelength. You can think of a narrow spectrum LED emitter as sitting near the edge of the chromaticity diagram, while phosphor converted LEDs including different whites along with mint and lime are closer to the center. The total range of colors a fixture can produce are determined by the gamut of its emitters. A simple way to think of it is to locate the emitters on the diagram and draw a polygon around the perimeter. Any color inside the polygon can be made by the fixture, anything outside the polygon cannot. Total fixture SPD equates to a combination of the individual emitter powers.

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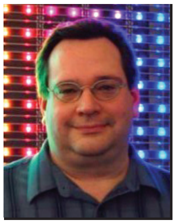
As we get closer to the middle of a chromaticity diagram the number of SPDs that can create a color at a specific set of coordinates becomes very large. A fixture with several overlapping emitter SPDs might be able to produce the same color coordinates using different combinations of emitter power. This is important because lighting the same material from sources with different SPDs can give different results, even when both are set to the same chromaticity coordinates. To some extent this depends on the precision of the controls, though. Think of each set of chromaticity coordinates as a square, with the exact coordinates in the center. Fixtures with different SPDs might fall inside that square when set to the same coordinates but still be different places inside the square. While using smaller squares sounds like an easy answer it is very difficult to achieve in practice. Even if the fixtures use the same LED chips, any differences in the drive circuits, the age of the LEDs, the operating temperature, and other factors in the fixture can affect the appearance of the material. Control resolution determines the size of the smallest square that can be sent from controller, regardless of what the fixture can produce.

The Photometrics Working Group has developed standard *ANSI E1.54* that addresses the protocol aspects of chromaticity control. *E1.54* uses only the *CE1931* chromaticity diagram, eliminating any issue of color space selection, and also defines the data structure for communicating coordinates over DMX512 in either 8- or 16-bit depth. Where supported by the fixture, it is best to use 16-bit, and use an interface that makes full use of that resolution. This gives the smallest square on the chromaticity diagram. Having *E1.54* is the first step, and hopefully fixture and controls manufacturers will follow by quickly implementing the 16-bit format.

When fine tuning color I find it helpful to use chromaticity coordinates to get into the right area, then I'll switch to direct emitter control for fine tuning. That allows precise selection of the SPD that brings out the most vivid colors. Perhaps as more products implementing the 16-bit format of *E1.54* come into the market that fine tuning step won't be needed as much, but at present that process works well.

Here I've gone into depth on how to avoid color problems with LED fixtures. Narrow spectrum LEDs also offer new artistic opportunities. Taking advantage of those opportunities does require an understanding of the basics outlined here. Once past the problems, a rainbow of new design possibilities opens before us. ■



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