LEDs MAGAZINE

Accurate modeling of LED colors: a scientific approach

LED light sources are being used more frequently in large-scale applications, but planning them can be hampered by poor color rendering on computer screens. **Ian Ashdown** of byHeart Consultants Limited discusses methods for improving on-screen color accuracy.

As architects embrace multicolor LED-based luminaires for architectural and entertainment applications, we as lighting designers are faced with a problem. We can offer computer-generated renderings to our clients, but it is often difficult to produce realistic colors.

One of the problems is that lighting design programs allow us to specify the color of light sources. This is great, except that we need to know what colors to use for modeling real-world LEDs.

Our first attempt is usually to do this:

- Red: (1.00, 0.00, 0.00)
- Green: (0.00, 1.00, 0.00)
- Blue: (0.00, 0.00, 1.00).

Here, we have assumed that "red is red" and so forth. However, we quickly learn that the "green" is too yellowish, and that in general the rendered colors do not appear very realistic when compared with color photographs of finished solid-state lighting installations. If the renderings are meant to show the client what the project will look like, this is not an auspicious beginning.

The second attempt – often done in a panic as deadlines loom – is to determine approximate color values through trial and error. For example, we might take a color photograph and attempt to match the red, green and blue colors with those displayed on our video displays.

This is a risky approach, as in general we do not know whether the LED luminaires were generating single colors, and we do not know the colors of the surfaces they were illuminating. Still, it is better than the first attempt.

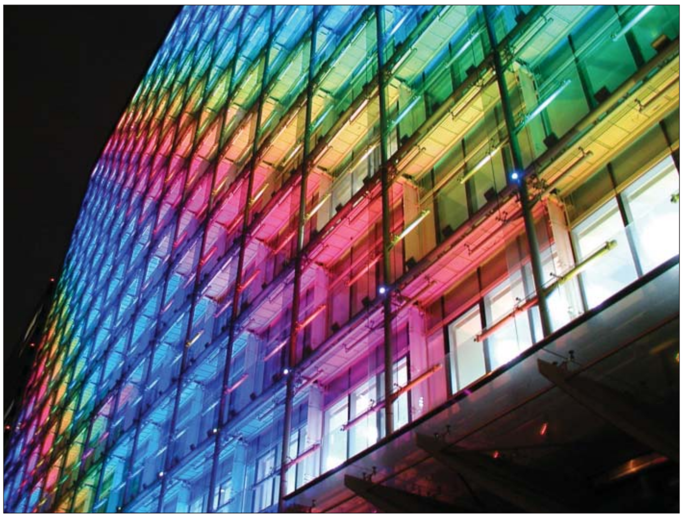
Our third attempt... well, let's take the scientific approach and do it properly.

Plotting colors

We already know that we can generate most colors by combining red, green and blue light. This is after all how both multicolor LED luminaires and color video displays work. Our problem is that the CRT display phosphors (and their equivalent LCD display color filters) do not produce the same colors as do red, green and blue LEDs.

We can visualize this problem by plotting the colors on the CIE 1931 *xy* chromaticity diagram. Most CRT displays use ITU-R BT.709 phosphors with the *xy* chromaticity coordinates shown in the table "ITU-R BT.709 phosphor properties". (LCD displays use color filters rather than phosphors, but they have similar chromaticity coordinates.)

Plotting these colors on the CIE chromaticity diagram gives a triangle that defines the color gamut for the display (figure 1). By mixing various amounts of red, green and blue, we can generate any color contained within this triangle. What we cannot do is generate colors



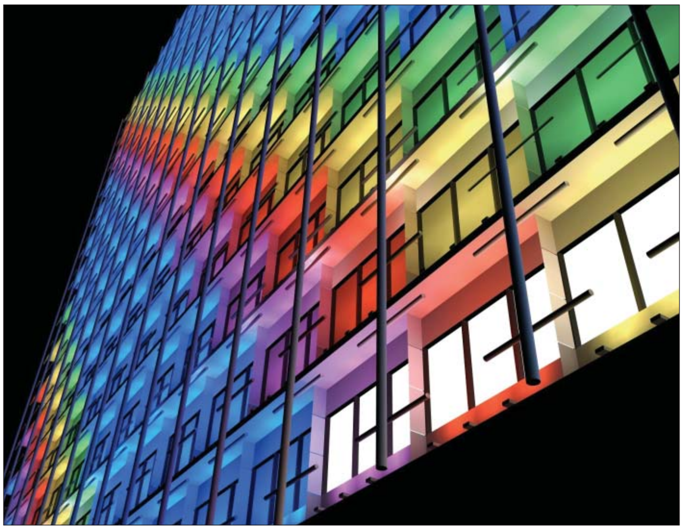


Photo of the Kuo Hua Commercial Insurance Building in Taipei, Taiwan (top), and a design rendering of the same building (bottom). (Photo courtesy of TIR Systems Ltd.)

that lie outside the color gamut of the CRT or LCD display.

Now, what about red, green and blue LEDs? Well, one problem is that their chromaticity coordinates typically lie outside of the color gamut of CRT and LCD displays. For example, a Lumileds Luxeon

ITU-R BT.709 phosphor properties

Phosphor	x	y
Red	0.640	0.330
Green	0.300	0.600
Blue	0.150	0.060

Data refers to xy chromaticity co-ordinates of ITU-R BT.709 phosphors which are used in most CRT displays [1].

RGB values for Luxeon LEDs

LED color	Dominant wavelength λ_D (nm)	RGB values
Royal blue	455	0.05, 0.00, 0.95
Blue	470	0.00, 0.11, 0.89
Cyan	505	0.00, 0.63, 0.37
Green	530	0.00, 0.77, 0.23
Amber	590	0.70, 0.30, 0.00
Red-orange	615	0.97, 0.00, 0.03
Red	625	0.92, 0.00, 0.08

green LED may have chromaticity coordinates $x = 0.288$ and $y = 0.710$.

We can however approximate this color by drawing a line from the white point through the LED color to the spectral locus (the horseshoe-shaped curve). The color on the spectral locus represents a fully saturated color that has a specific wavelength (measured in nanometers) of the visible spectrum.

As we move closer and closer to the white point along the line, the corresponding color has approximately the same hue, but it becomes more and more desaturated as we add increasing amounts of white light.

The specific wavelength is called the dominant wavelength λ_D of the LED, and it is the metric that LED manufacturers use to bin their color LEDs. Lumileds, for example, bins its blue and green LEDs at 10 nm intervals.

While we cannot reproduce the green LED color on a CRT or LCD display, we can generate a desaturated color with the same hue. Referring once again to our line, this is the line's intersection with the display's color gamut triangle.

One of the advantages of the CIE 1931 *xy* chromaticity diagram is that it is linear. For example, the relative distance of the desaturated green LED color from the blue and green phosphor colors represents the ratio of blue and green for the corresponding RGB triplet we need to describe the light source color. In the example shown in figure 1, the RGB values are: (0.0, 0.7, 0.3).

Our problem therefore has a simple geometric solution. If we know the average dominant wavelengths of the LEDs in a multicolor LED-based luminaire, we can determine the equivalent RGB values needed to model the LED colors in our lighting design program.

All we need are the chromaticity coordinates of the white point...

White points

As lighting designers, we know that fluorescent lamps have different color temperatures, and yet we refer to them as "white light" sources. Not surprisingly, the same concept and terminology applies to CRT and LCD displays. When a display generates "white" (which is its white point), the color has a specific color temperature.

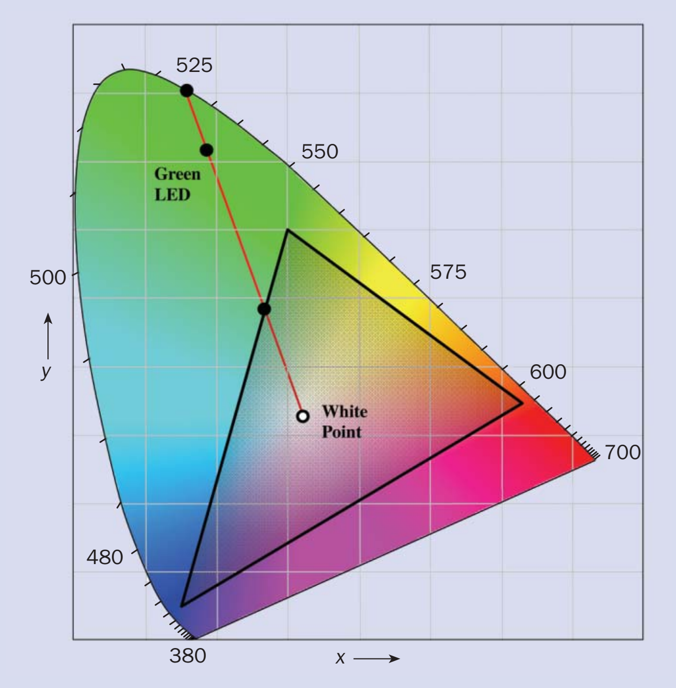


Fig. 1. Video display color gamut on the CIE *xy* chromaticity diagram.

For many years, CRT displays had a color temperature of 9300 K – a "white" that we would find intolerably blue as a fluorescent light source. The reason is historical; blue phosphors were more efficient than red and green phosphors, and so CRT display manufacturers opted for a high color temperature in order to maximize the display luminance.

The situation has changed since the introduction of LCD displays, which typically have a color temperature of 6500 K (which is close to daylight on a clear day). Most modern CRT displays now provide the option of either of these settings for their white point.

So we apparently have a choice of chromaticity coordinates for our white point:

- 6500 K (0.313, 0.329)
- 9300 K (0.283, 0.297).

Color constancy

Why "apparently?" Well, there is one more complication. Most lighting design programs implicitly assume that the color temperature of "white" light sources (including daylight) is 6500 K. When we view the computer renderings on a 9300 K CRT display, we are viewing what should be 6500 K white as a much bluer 9300 K white. All other displayed colors are similarly affected – it is as if we were viewing the scene through a light blue color filter.

This however is not a problem, as color constancy comes to our rescue. We mentally subtract the overall bluish color cast and see the rendering in what appear to be its "true" colors.

It therefore makes sense to assume 6500 K as our white point, regardless of the actual display color temperature. This will allow us to view the renderings without being concerned about the display properties.

With this, we can determine the equivalent RGB light source values for typical LED dominant wavelengths. The calculations are straightforward but somewhat tedious. However, we can choose representative Lumileds Luxeon products by noting that other manufacturers' LEDs will have similar dominant wavelengths. Performing the calculations for these products, we obtain equivalent RGB values as shown in the table "RGB values for Luxeon LEDs".

Digital cameras

We are almost done. Although we have taken the scientific approach to modeling RGB colors, there may still be visual discrepancies between our renderings and digital photographs of the finished installation. Why is this? There may be many reasons, but here are some key points to keep in mind:

- The spectral (color) responsivity of digital cameras usually differs from that of the human eye.
- The camera may automatically adjust its white point according to the scene content, and it may not assume a 6500 K illuminant.
- The display device must be properly calibrated using color management techniques and hardware for side-by-side comparisons.
- The illuminated surfaces in the digital photograph may have different colors than those assumed for the computer model.

These are all color management issues, which require entire books to properly explain [2]. It is possible to adjust CRT or LCD displays such that colors within their color gamuts will appear the same on each device. However, it is generally not possible to calibrate digital cameras except when used under carefully controlled studio lighting conditions.

Lighting design and color

Multicolor LED-based luminaires have brought vibrant and dynamic colors to our lighting designs. By taking a scientific approach to modeling LED colors, we can minimize the differences between what our computer renderings show and what the client will see with the finished project. It may not be precisely "what you see is what you get," but we can come as close as today's display technologies allow.

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References

1 ITU-R Recommendation BT.709, *Basic Parameter Values for the HDTV Standard for the Studio and for International Programme Exchange* (1990).

2 See for example B Fraser, C Murphy and F Bunting 2005 *Color Management, Second Edition* (Berkeley, CA: Peachpit Press).

Acknowledgment

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