LED Color Mixing: Basics and Background

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INTRODUCTION

This application note explains aspects of the theory and practice of creating color-consistent, LED-based illumination products and shows how to use Cree XLamp® LEDs to achieve this end.

LEDs, as with all manufactured products, have material and process variations that yield products with corresponding variation in performance. LEDs are binned and packaged to balance the nature of the manufacturing process with the needs of the lighting industry. Lighting-class LEDs are driven by application requirements and industry standards, including color consistency and color and lumen maintenance. Just as traditional lamps are sold by brightness (typically indicated by wattage) and color (warm or cool white), LEDs are binned for brightness (luminous flux) and color parameters (chromaticity).

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THE NEED FOR COLOR CONSISTENCY IN LED ILLUMINATION

There is nothing like a picture to illustrate a visual point such as color variation. The photograph in Figure 1 clearly shows the need for every illumination technology to deliver consistent color. This photograph is an example of the challenges Cree, in conjunction with the lighting industry, is trying to meet for LED lighting applications.

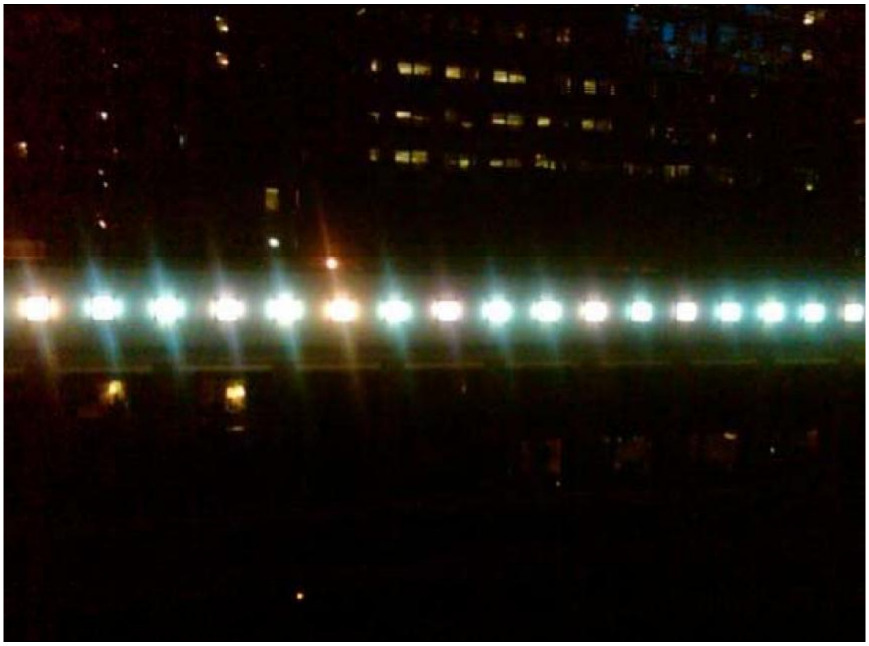


Figure 1: The need for color consistency spans all illumination technologies

Figure 1 is a photograph of an array of high-intensity discharge (HID) lamps illuminating the facade of a building. It shows the undesirable results of inconsistent color temperature and the degradation of performance of luminaires as they age.

Increasingly active industrial policy in the United States and throughout the world is resulting in a rigorous set of performance requirements for LED lighting applications. The first industrial policy that mandated illumination technology for LED lamp requirements was the 2007 document, "ENERGY STAR® Program Requirements for Solid State Lighting Luminaires." This was followed by requirements for LED lamps, enumerated in the 2010 document "ENERGY STAR® Program Requirements for Integral LED Lamps", which proposed stringent requirements, significantly above those for compact fluorescent lamp (CFL).[1] Each of these documents contains requirements for correlated color temperature (CCT), color rendering index (CRI), lumen and color maintenance for an ENERGY-STAR-approved LED illumination product and have been subsequently revised[2,3]. CCT requirements are excerpted in Tables 1 and 2 below.

1 See www.energystar.gov/ia/partners/prod_development/revisions/downloads/cfls/Criteria_CFLs_V4.pdf
2 www.energystar.gov/ia/partners/product_specs/program_reqs/Integral_LED_Lamps_Program_Requirements.pdf
3 www.energystar.gov/ia/partners/product_specs/program_reqs/Final_Luminaires_V1_2.pdf?7b7d-2473

Table 1: ENERGY STAR requirements for integral LED lamps, per program requirements (V1.4)

<table>
<tr><th>Characteristic</th><th colspan="3">Requirement</th><th>Reference Standard/Test Method</th><th>Sample Size/ Specific Requirements</th></tr>
<tr><td rowspan="3">CCT and Duv</td><td colspan="3">Lamp must have one of the following designated CCTs (per ANSI C78.377-2008) consistent with the 7-step chromaticity quadrangles and Duv tolerances below.</td><td rowspan="3">IES LM-79-08

ANSI/NEMA/ ANSLG C78.377-2008</td><td rowspan="3">10 units per model
• 5 base-up
• 5 base-down
At least 9 of the 10 samples must meet the specification</td></tr>
<tr><td>Nominal CCT</td><td>Target CCT (K) and Tolerance</td><td>Target Duv and Tolerance</td></tr>
<tr><td>2700 K
3000 K
3500 K
4000 K</td><td>2725 ± 145
3045 ± 175
3465 ± 245
3985 ± 275</td><td>0.000 ± 0.006
0.000 ± 0.006
0.000 ± 0.006
0.001 ± 0.006</td></tr>
</table>

Table 2: ENERGY STAR CCT requirements for indoor LED luminaires, per program requirements (V1.2)

Characteristic	Requirements
CCT requirements: all indoor luminaires	The luminaire (directional luminaires), or replaceable LED light engine or GU24 based integrated LED lamp (non-directional luminaires) shall have one of the following nominal CCTs: • 2700 Kelvin • 3000 Kelvin • 3500 Kelvin • 4000 Kelvin • 5000 Kelvin (commercial only) The luminaire, LED light engine or GU24 based integrated LED lamp shall also fall within the corresponding 7-step chromaticity quadrangles as defined in ANSI/NEMA/ANSLG C78.377-2008.

These requirements highlight the need to achieve defined, repeatable results with the manufacturing output from an LED supplier.

LED BINNING

LEDs can be characterized in multiple ways. For color mixing, the two most important dimensions are color expressed as chromaticity (CCx, CCy), and luminous flux, measured in lumens (lm). These parameters are collected as part of the LED component manufacturing process and are the basis for the component binning discussed in this document.

COLORIMETRY AND BINNING BASICS

It is easier to explain the world of LED colorimetric binning and mixing by reviewing a bit of high-level color science. Colorimetry is the science of the human perception of color and contains a framework for analyzing both the spectral distribution of illumination and the human characteristics of color perception.

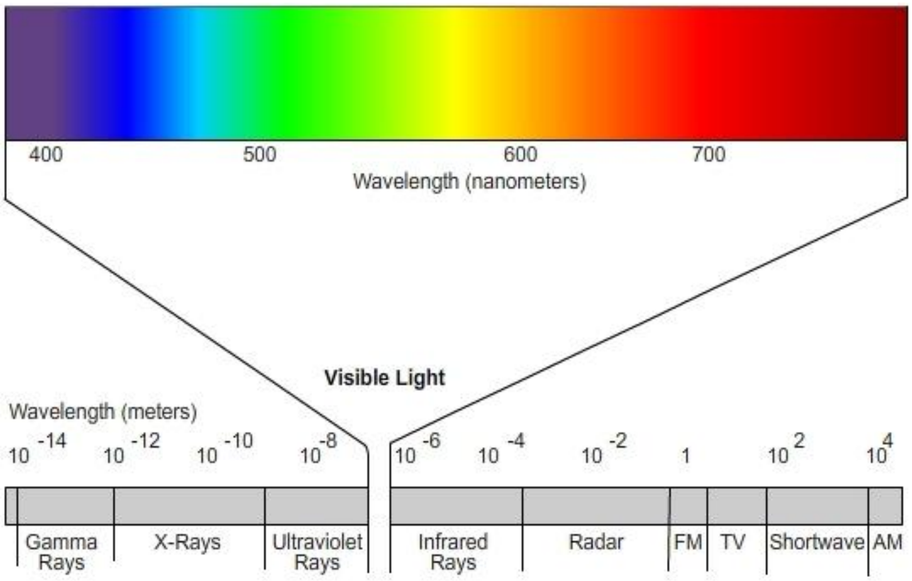


Figure 2: Light is the visible portion of electromagnetic spectrum ranging from 380 nm to 780 nm

A lighting designer may seek to deliver a warm, neutral or cool illumination source. Knowledge about the lighting application will allow the designer to ensure the correct lighting decisions are made for that space. Understanding the following key concepts that relate colorimetry and LED binning will enable the designer to specify the proper LED solution.

1. Color space, the formalism to objectively describe any perceptible color.
2. Color temperature, more precisely the correlated color temperature, characterizes the hue of an illumination source as a temperature on the Kelvin scale.
3. The empirical data and models of human perception and variability in color and vision that provide additional framework for the way in which color bins are created.

The perceptual psychologists' notion of the "just-noticeable difference" is the subjective threshold of perceptible change in any mode of the human senses. This has been key in understanding variation in human perception. David MacAdam, a color scientist working for Kodak during the mid-20th century, introduced a method to the "just-noticeable difference" notion. His work characterized human population variation and individual temporal variation in color perception, along with mapping these differences onto the color space.

Color-Space Basics

The science of color begins with the physiological constructs of the human retina's perception of light and color. Based on the perception of color by the human eye, models and objective criteria for the quantification of chromaticity are derived. The most commonly used model is the 1931 CIE color space, a methodology for mapping perceived color onto the unit plane of an x, y graph. This graph of x, y values for chromaticity is a mapping of perceived color expressed as a ratio of red, green, and blue colors. These three colors, i.e., the tristimulus values, correspond to the band-pass filtered chromaticity response of cones in the human retina. Using this chromaticity mapping allows the expression of any perceived hue or color as a simple locus on a unit plane. This has become one of the primary sorting, or binning, mechanisms for LEDs.

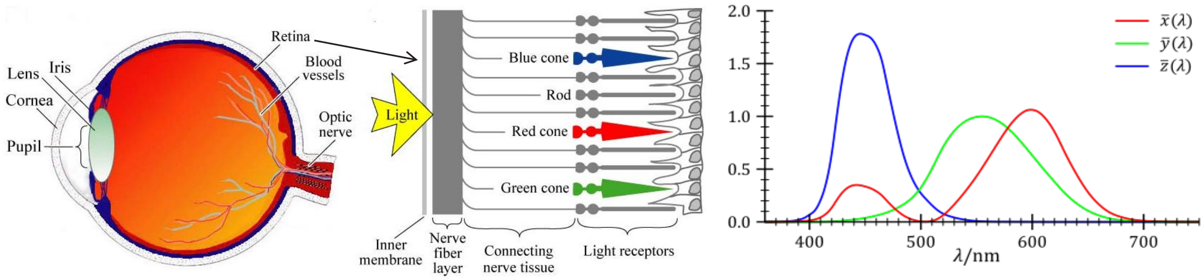


Figure 3: The human eye as the source of photopic response

Figure 4 below shows an enhanced version of the 1931 CIE chromaticity diagram.

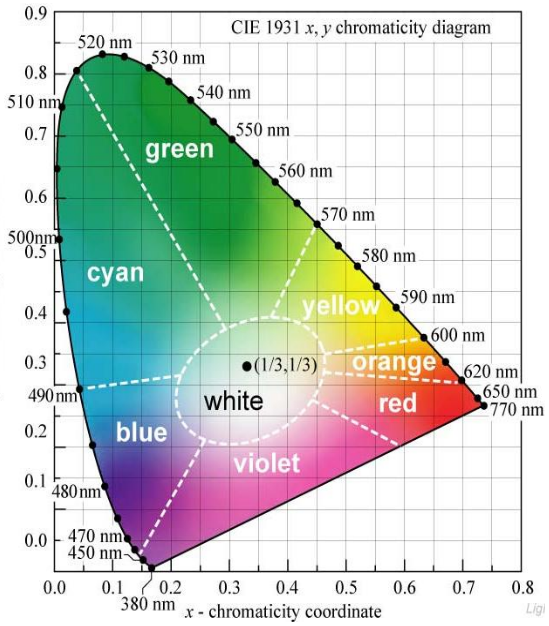
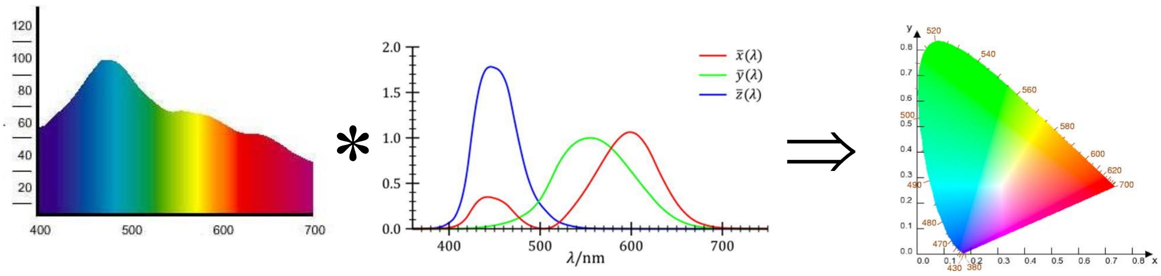


Figure 4: 1931 CIE Chromaticity Diagram

Pure or saturated colors are located around the perimeter of the paraboloid and white light is located at its center. In illumination applications, white will be a region around the center of the diagram and binning will correspond to small, enclosed regions around the white center of the color space.

The transformation illustrated in Figure 5 shows how to derive a chromaticity coordinate from the radiometric signature, or spectral power distribution, of an illumination source.



$$P(\lambda) \Rightarrow \begin{aligned} X &= \int_\lambda \bar{x}(\lambda)P(\lambda)d\lambda \\ Y &= \int_\lambda \bar{y}(\lambda)P(\lambda)d\lambda \\ Z &= \int_\lambda \bar{z}(\lambda)P(\lambda)d\lambda \end{aligned} \Rightarrow \begin{aligned} x &= \frac{X}{X+Y+Z} \\ y &= \frac{Y}{X+Y+Z} \end{aligned}$$

Figure 5: How to derive x, y values for a light source

Each type of retinal cone has one of three sensitivities to dominant red, green, or blue wavelengths. This is another way of saying human vision is trichromatic. X, Y and Z are the trichromatic "responses" of the cones to a given illumination signal. The derivation of these formulae can be found in any number of textbooks,[4] and are presented here to give the framework for the practical algebra of color mixing that is presented later in this document.[5]

A key aspect of colorimetry is that color perception is essentially an additive function of the color space. Human color perception can be such that two light sources made up of different wavelengths may appear to be the same color. Thus two light sources will have the same apparent color to an observer when they have the same tristimulus values, no matter what spectral distributions of light were used to produce them. Two sources that have the same trichromatic values will also have the same resulting chromaticity point in the color space.

To create white light from multiple sources with varying wavelengths and intensities, LED manufacturers utilize the principles of visual perception.

1. The perceived color of any light source or reflected color can be defined as a location on the color space.

2. Two illumination sources with widely varying spectral profiles can elicit the same (perceived) value in the color space.

Figure 6 below shows that multiple configuration of phosphors and LEDs can be tailored to deliver the same x, y coordinate in the CIE color space. The spectral profile of each configuration is significantly different but the viewer perceives the same apparent color.

4 For example, an efficient presentation of this material can be found in Chapter 17 of Schubert's *Light Emitting Diodes*, 2nd Ed.

5 In like manner, brightness or luminous flux is an additive value and is part of the color mixing algebra. It is derived from the photopic response of the green cones.

$$\Phi(lumens) = 683\,\frac{lm}{W} * \int_{380nm}^{780nm} P(\lambda) * Y(\lambda)\, d\lambda = Y$$

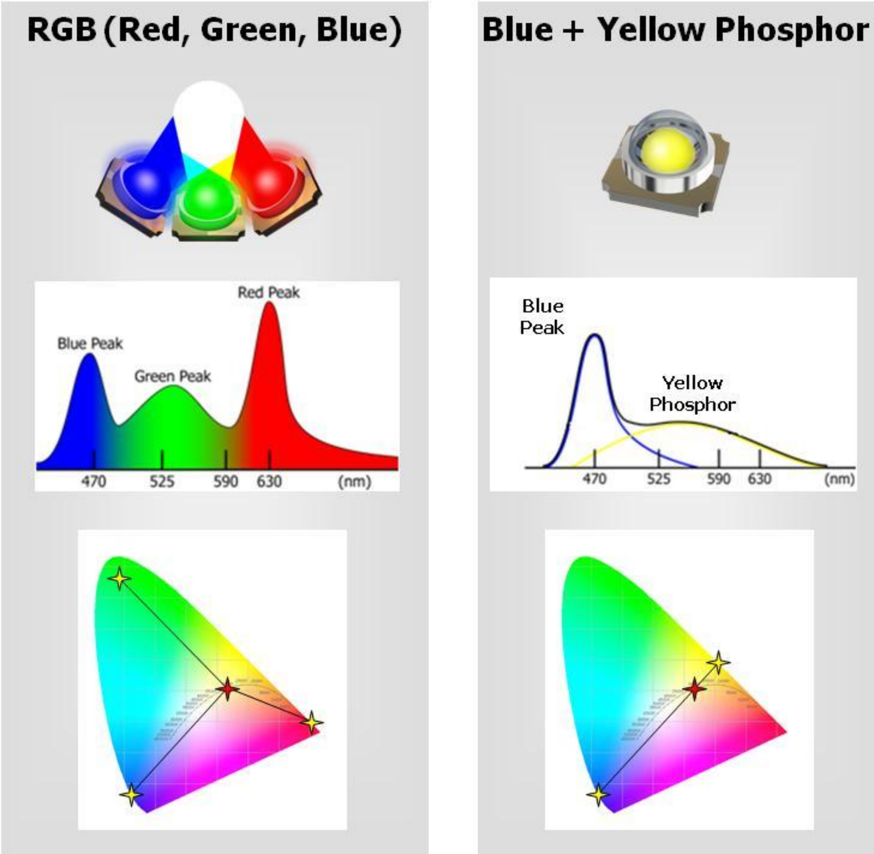


Figure 6: Two ways to produce white light with LEDs

Idealized Illumination Colors – the Black Body Curve

In addition to the CIE color space, another important idea is CCT. The physics behind this system, formalized as a temperature scale in the latter 20th century, was worked out in the realm of quantum physics and the spectral emissions of an idealized black body radiator. This idealized object emits radiation when heated and a portion of the resulting spectra is visible light over a very high temperature range and is illustrated in Figure 7.

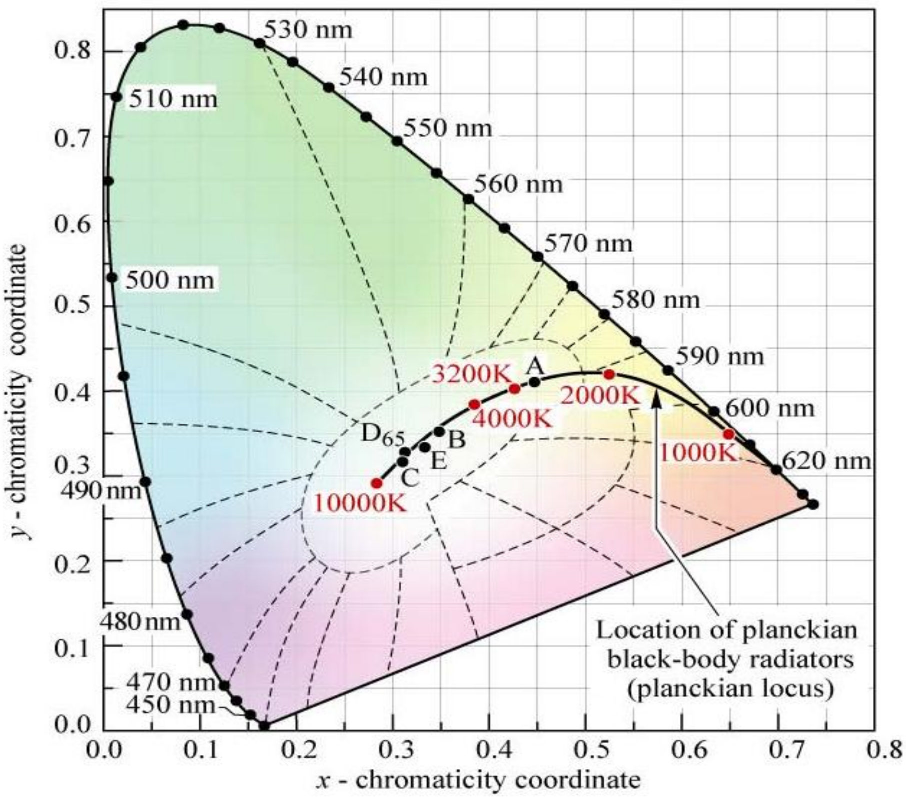


Figure 7: CIE chromaticity mapping with black body line[6]

This is intuitive when we see metals glow red, then yellow, then white as they are heated. The black body line or Planckian locus gives a single metric to characterize an illumination source, the CCT, expressed as Kelvin (K).

CCTs of 2700-3000 K are described as warm white, occupying a region with a yellower hue of white. CCTs of 3500-4000 K are described as neutral white and CCTs of 4500-5500 K are described as cool white, for their bluish hue.

6 www.ecse.rpi.edu/~schubert/Light-Emitting-Diodes-dot-org/chap18/F18-03%20Chromaticity%20diagram%20-%20planckian.jpg

MacAdam Ellipses: The Variability of Perception, Expressed in Color Space

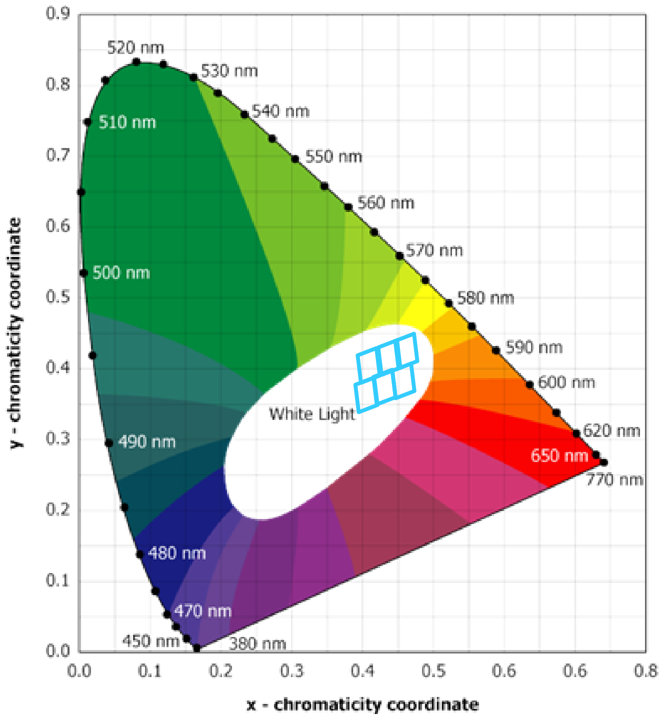


Figure 8: Color bins in the color space

The CIE color space allows an objective way to express color, since no two humans perceive color in exactly the same way. For that matter, an individual's perception of color varies over time. So how can we come to an acceptably uniform definition of color from the human eye's perspective?

David MacAdam devised a set of viewing experiments that documented the variability of color perception in single viewers. The results of his work showed that individual viewers tended to cluster their perceptions of similar colors into ellipses on the CIE color space, illustrated in Figure 9.

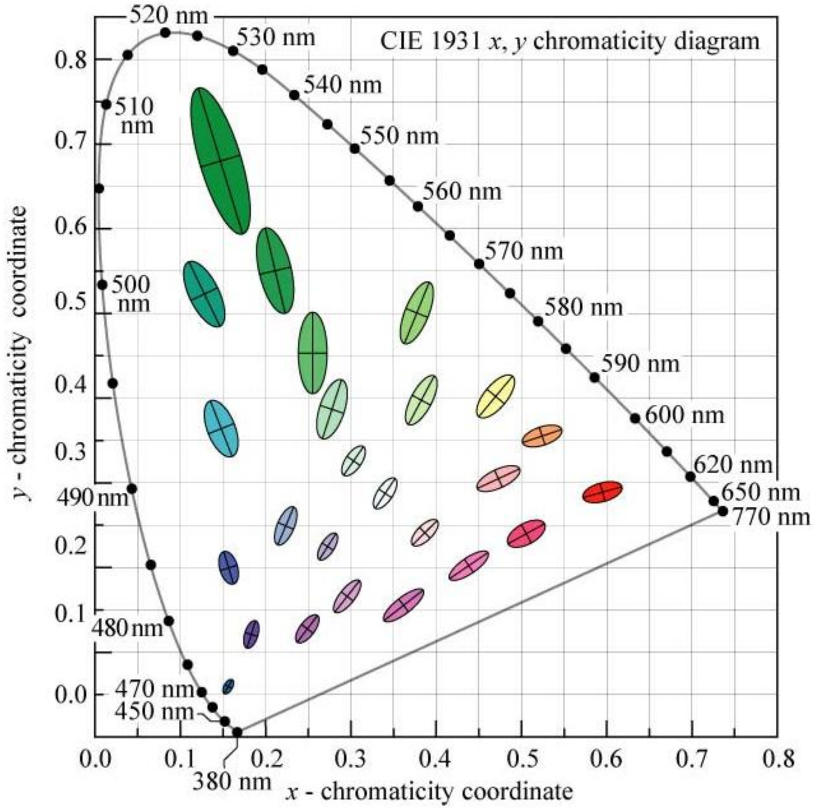


Figure 9: MacAdam ellipses

MacAdam generalized these ellipses to human populations, and asserted standard statistical variance of perception can be mapped onto the color space as well. In practical terms, a MacAdam ellipse for a particular color point is defined to encompass one standard deviation of a “standard observer.” Roughly 65% of the population would situate or place their perception of the same color as a point within a MacAdam ellipse. Larger ellipses can be defined to enclose two, three or more standard deviations allowing a higher percentage of observers, 95% to 99%, to perceive the same color as a point somewhere within these ellipses.

Color bins are defined as parallelograms in the 1931 CIE color space. Why? The parallelograms used by ANSI to define the color bins are sized and oriented to approximately enclose a MacAdam ellipse whose center is at a particular locus on the color plane.

The LED binning defined by ANSI in the C78.377-2008 standard encloses a 7-step MacAdam ellipse, originally defined for CFLs. These bins are centered on the black body line. Figure 10 below shows an illustration from the standard.

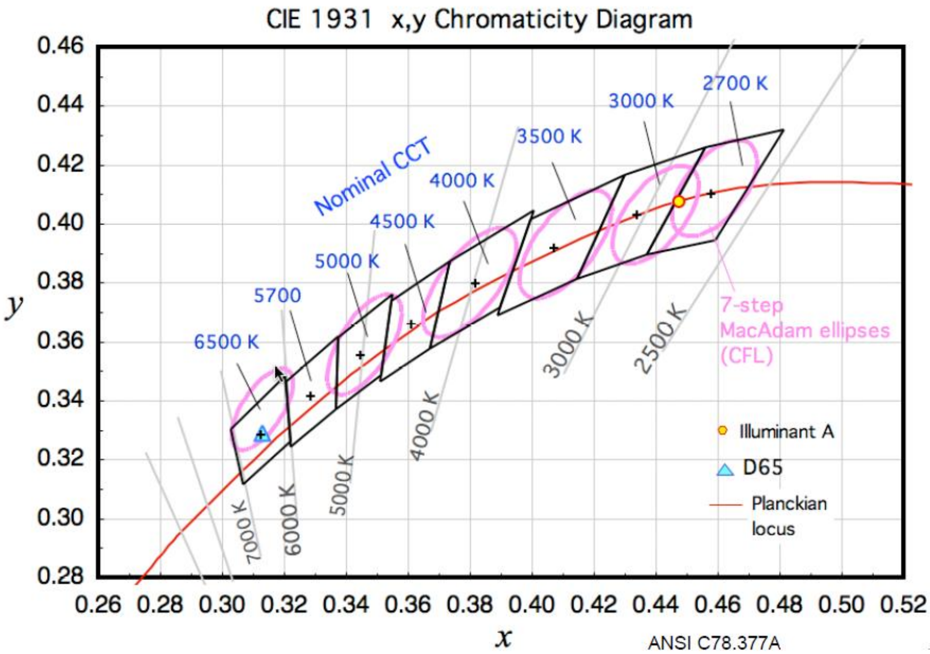


Figure 10: An illustration from the ANSI C78.377-2008 standard[7]

Partitioning the Color Space – Binning

Phosphor-based illumination sources exhibit greater variability than other sources such as tungsten or halogen. Binning systems first emerged to characterize phosphors and more recently to characterize white LEDs. LED manufacturers adopted binning techniques to offer consistent characterization of their manufactured output.

Though manufactured to exceedingly tight tolerances at every step from wafer production to component packaging, there are natural variations in material and processes that dictate the photometric properties of white LEDs. Material characteristics vary over the surface of a wafer and so into the individual LED die. Binning characterizes the output of manufacturing processes and lets customers develop strategies to work with this output and achieve uniform illumination sources. Cree's basic binning nomenclature and definitions follow the ANSI C78.377-2008 LED binning standard. The location, shape, and size of these bins have a rough conformance to the varying axial orientation and sizes of MacAdam ellipses.

In response to demands of the lighting industry, LED manufacturers have rapidly improved product uniformity and distribution. Cree developed the XLamp LED bins by segmenting the ANSI bins in an effort to reduce color variation.

Figure 11 shows an example of the bin of a 3200-K product and illustrates a practical example of the bins. The center of the bin is (0.4245, 0.3999) around the intersection of the black body line and the 3200-K gradient line. The boundaries of the parallelogram are displayed in the illustration.

7 NEMA ANSI ANSLG C78.377-2008, "Specifications for the Chromaticity of Solid State Lighting Products for Electric Lamps"

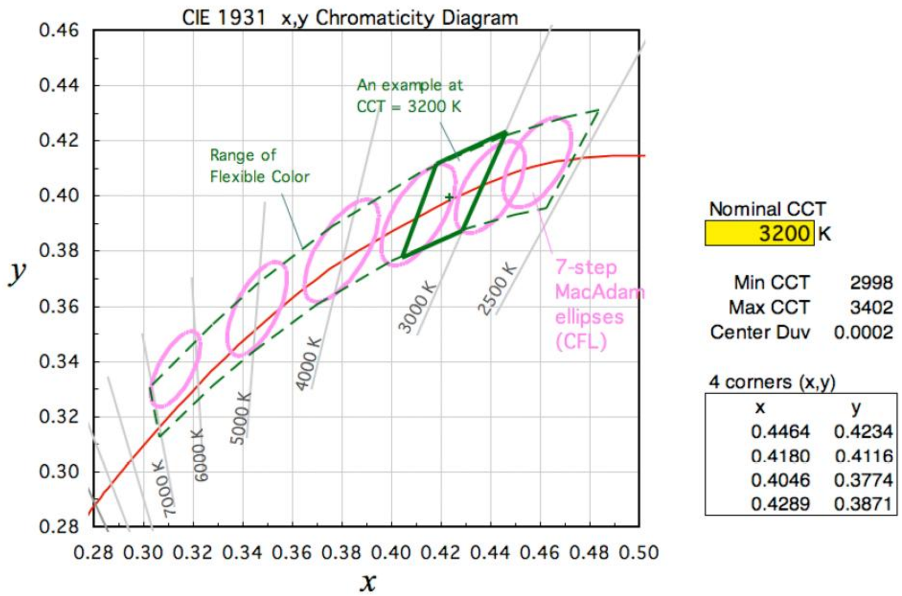


Figure 11: An example at 3200 K

Segmenting the ANSI bins allows for progressively tighter specification and increased product uniformity. This is illustrated in Figure 12 below. The light dashed line in the illustration is the black body line and the bins are clustered around it. The black dashed parallelograms represent the ANSI white bins as defined by the ANSI LED bins. The smaller red parallelograms are the Cree bins defined for XLamp white LEDs.

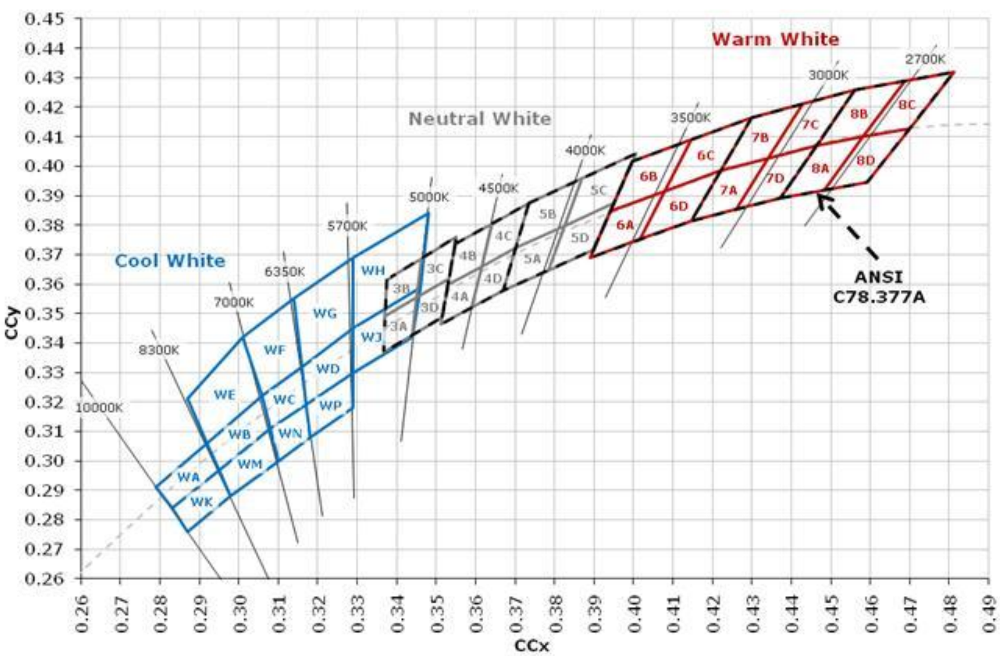


Figure 12: Cree XLamp LED binning structure

As shown in Figure 13, Cree further subdivides the standard XLamp LED bins for progressively finer granularity and better product control.

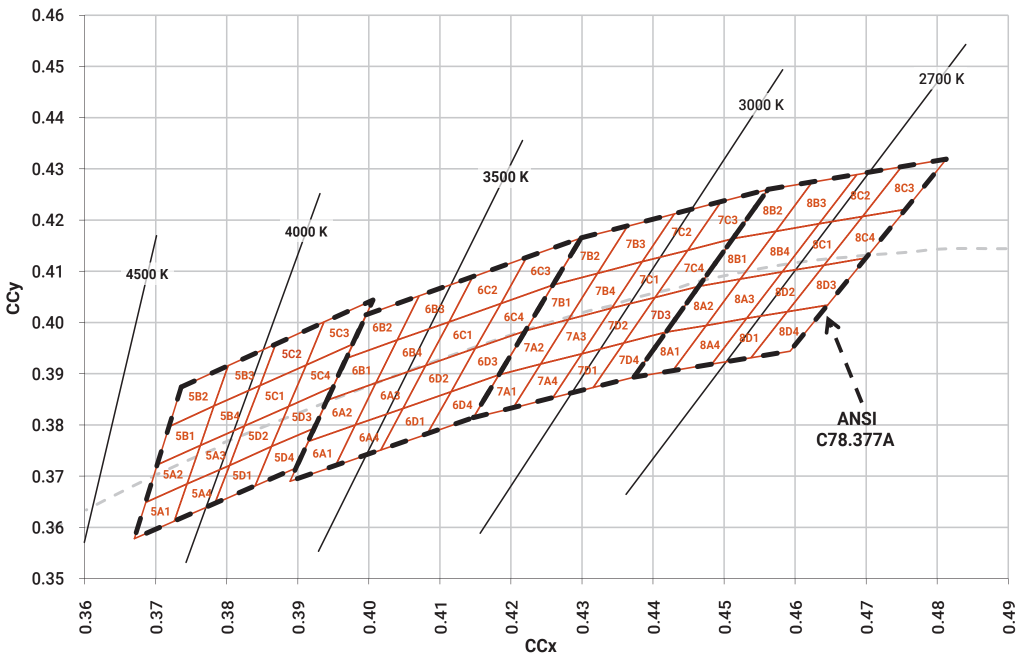


Figure 13: Cree XLamp LED warm-white bins

Chromaticity Bins

Cree provides industry-leading granularity by defining sub-bins within each of the ANSI C78.377 bins for warm-, neutral- and cool-white XLamp LED products.

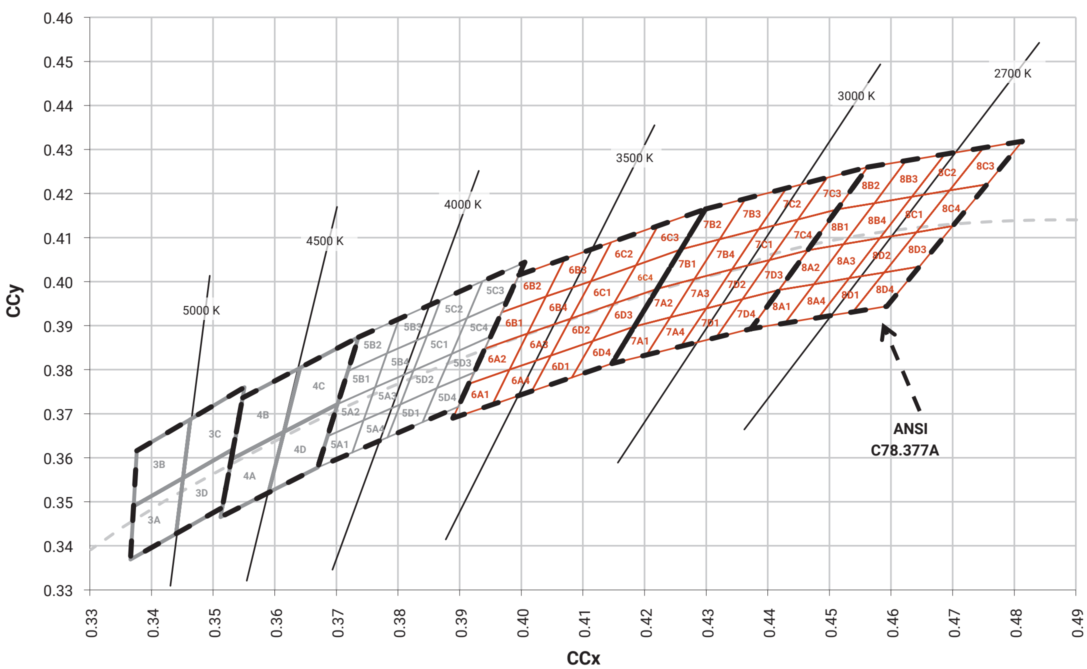


Figure 14: XLamp LED warm- and neutral-white bins

Cree XLamp LED products have two main technical support documents, both of which are available on the Cree website.

1. Data sheets provide electrical and luminous flux performance characteristics.

2. Binning and labeling documents provide details about chromaticity, luminous flux binning, and ordering information.

Beginning in December, 2009, Cree launched a version of a multi-die LED component, the XLamp MC-E EasyWhite™ LED. A second multi-die member of the EasyWhite binning family was announced with launch of the XLamp MP-L EasyWhite LED. Cree has subsequently released multi-die MT-G2, XM-L®, XM-L2, MK-R and MK-R2 EasyWhite LED components. EasyWhite represents a significant simplification in multiplying LED bins to achieve white light, as the map in Figure 15 below shows. Instead of dozens of chromaticity bins, there is only one chromaticity bin for each standard color temperature. This approach is unique in that each of the four bins are centered on the black body line.

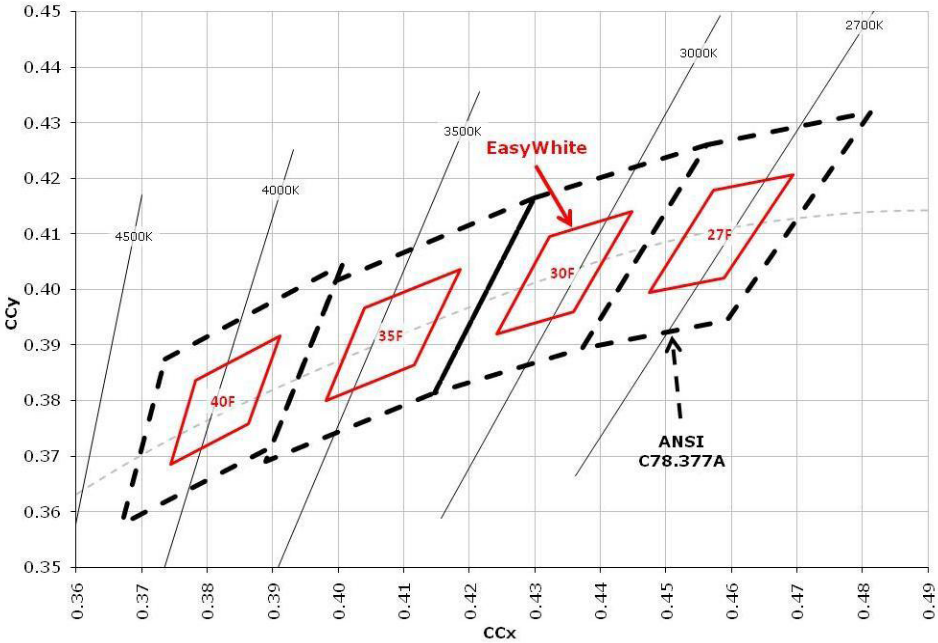


Figure 15: EasyWhite bins

Flux Bins

Luminous flux is an additive metric just as perceived color is additive. Many types of luminaires are created by laying out arrays of LEDs and summing the flux of the entire array.

Cree XLamp LEDs are also characterized by their luminous flux at a nominal current[8] and operating temperature.[9] An example of this categorization follows in Table 3.

8 Most often 350 mA
9 Most often 85 °C at the LED junction (active region of the component, calculated based on the thermal resistance and solder point temperature)

Table 3: Example of Cree flux bins

Flux Bin	Luminous Flux (lm)		Flux Bin	Luminous Flux (lm)	
	Minimum	Maximum		Minimum	Maximum
K2	30.6	35.2	Q3	93.9	100
K3	35.2	39.8	Q4	100	107
M2	39.8	45.7	Q5	107	114
M3	45.7	51.7	R2	114	122
N2	51.7	56.8	R3	122	130
N3	56.8	62.0	R4	130	139
N4	62.0	67.2	R5	139	148
P2	67.2	73.9	S2	148	156
P3	73.9	80.6	S3	156	164
P4	80.6	87.4	S4	164	172
Q2	87.4	93.9			

USING COLORIMETRY AND BINNING INFORMATION IN ILLUMINATION SPECIFICATION

To understand why multi-LED color mixing is an important and cost-effective manufacturing technique, consider the following hypothetical distribution of LEDs in a large production run.

A customer may specify a chromaticity requirement by a calling out a particular bin, say 7B4, a bin near the black body line around 3000 K. An LED production run will have a component distribution across similar color bins. Customers who area able to use a wider collection of color bins can expect to purchase their LEDs at a lower cost than customers who purchase only a particular bin.

In a given production run of LED components, luminous flux will vary over several bins, for example from flux bin Q5 through R2 from Table 2 above. Figure 16 below shows a hypothetical chromaticity variation in a production run. Some of the chromaticity bins have large populations and some the bins have no product at all.

No LED manufacturer can produce uniform color points in their white LEDs; rather, they produce batches of LEDs with varying distributions of color and flux to create inventory based on the results of the production.

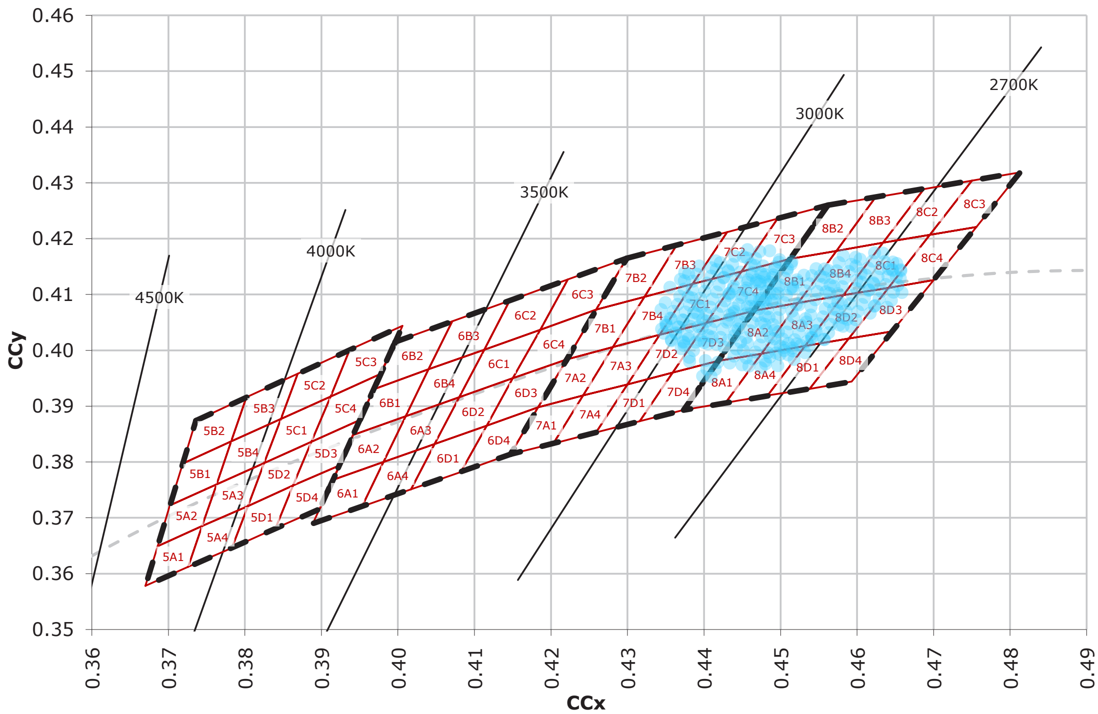


Figure 16: Hypothetical LED chromaticity distribution

Both chromaticity and flux are additive and this forms the basis of the techniques we demonstrate for creating color-consistent products from an inconsistent supply of LEDs.

Additive Nature of Photometry and Colorimetry

Every illumination source has a (radiometric) spectral power distribution whose output can be expressed as the integral of radiant power over the wavelength range of the light-emitting source. The eye's perception of this source can be expressed as a single chromaticity value, an ordered pair in a planar color-space (CCx, CCy). Finally, this value can be expressed as a CCT. Chromaticity results come from the physiologically based, additive nature of color perception. CCT is a categorization or binning of illumination sources, sorted into regions of warm-, neutral- and cool-white light.

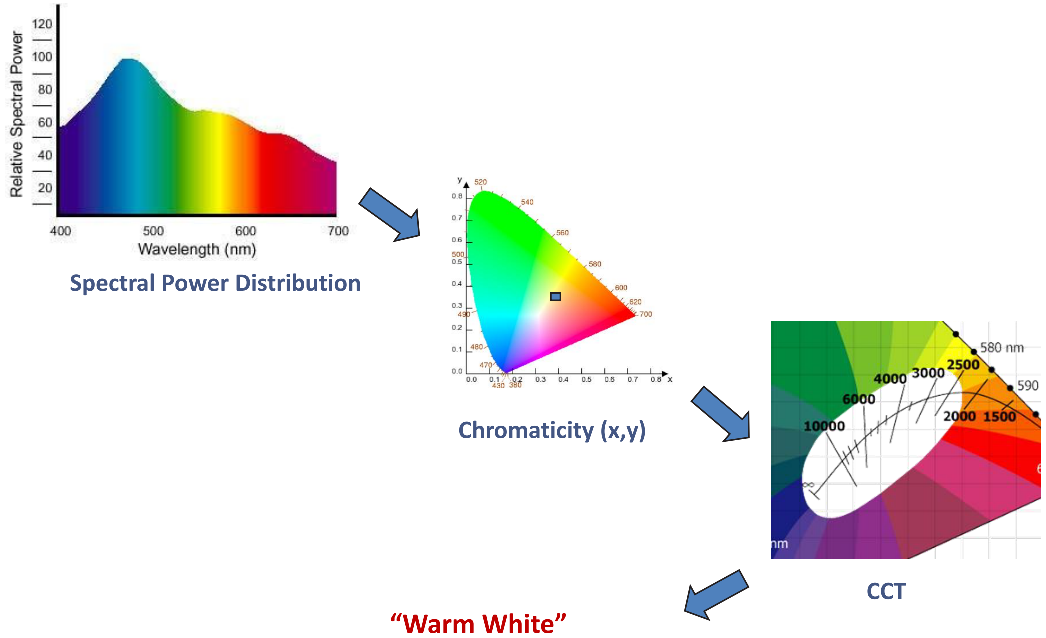


Figure 17: From the objective to the subjective

The Basic Approaches

There are three ways in which a company can work with Cree to procure LEDs to achieve color-consistent lighting products.

1. Buy one or a very small number of bins. The purchase of the same small collection of parts over and over is a reasonable and repeatable strategy, but due to nature of LED manufacturing, this is never the lowest cost way to procure a production supply of LEDs.

2. With the release of EasyWhite products, beginning in late 2009, Cree has made it possible for its customers to work with LEDs in a way that is similar to original bulb-specification practices, e.g., specifying just CCT and flux. Cree performs color mixing on behalf of its customers in building EasyWhite versions of select XLamp LED components.

3. The most cost-effective way to work with Cree is to buy full distributions of XLamp LEDs, i.e., the full manufacturing output of an LED production run, which includes variety in flux and chromaticity. To use full distributions effectively, the lighting manufacturer develops expertise in multi-LED illumination systems and color-mixing recipes. Color-mixing recipes offer numerous flexible solutions to create repeatable chromaticity results and can deliver a cost-competitive advantage over the first two approaches.

These approaches are illustrated graphically in the following sequence of illustrations.

THREE APPROACHES

Buy Single (or Few) Chromaticity Bins

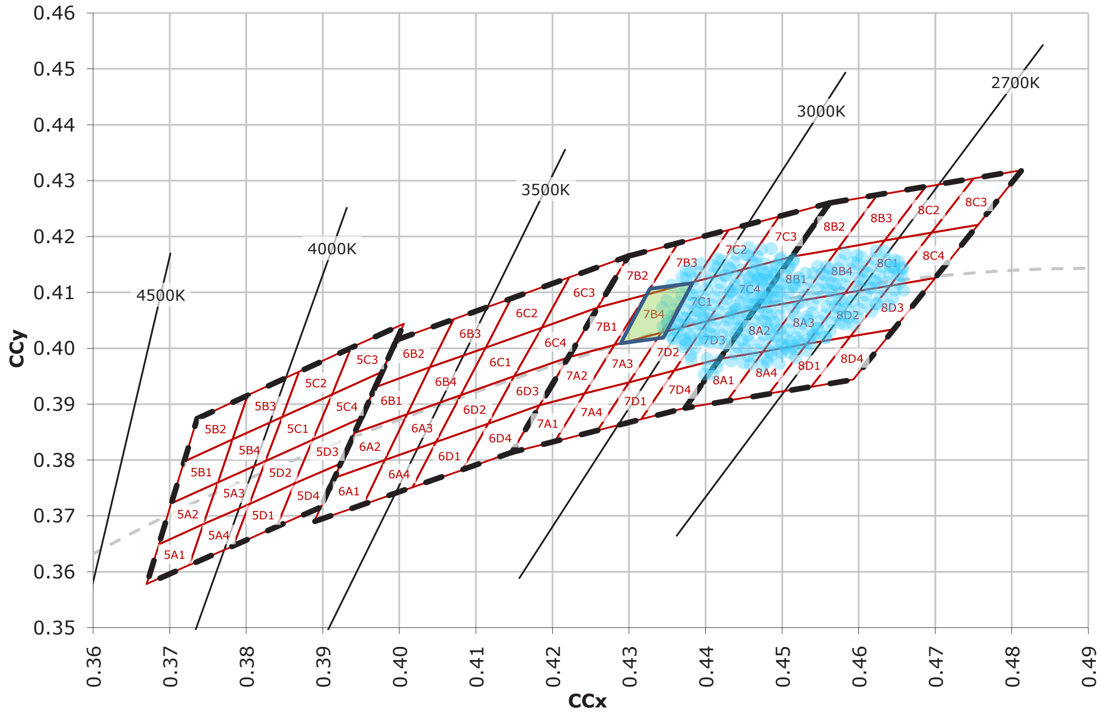


Figure 18: Buy single bins - a price-insensitive strategy

Use Cree EasyWhite Components

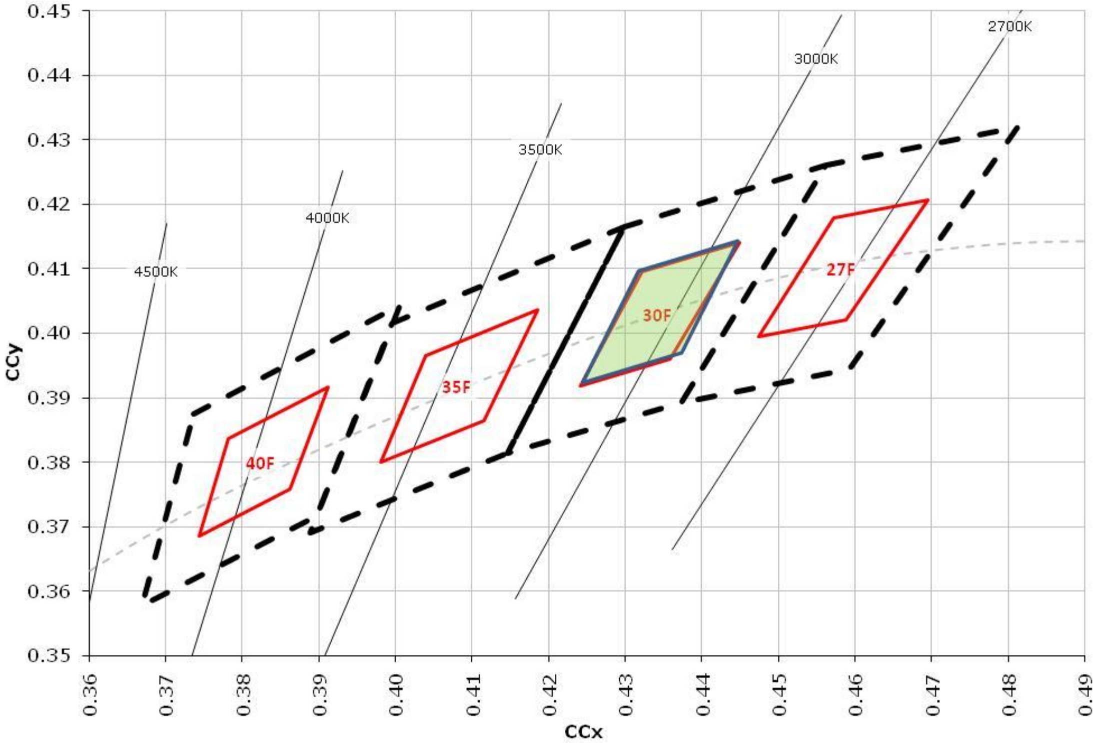


Figure 19: Buy EasyWhite bins, a structurally repeatable strategy

Color Mixing in the LED System

For some multi-LED applications, mixing white LEDs from a variety of bins is a cost-effective way to achieve good color quality while minimizing LED costs. This illustration shows four color-mixed LEDs can achieve the same perceived result as four LEDs from one of the central sub-bins.

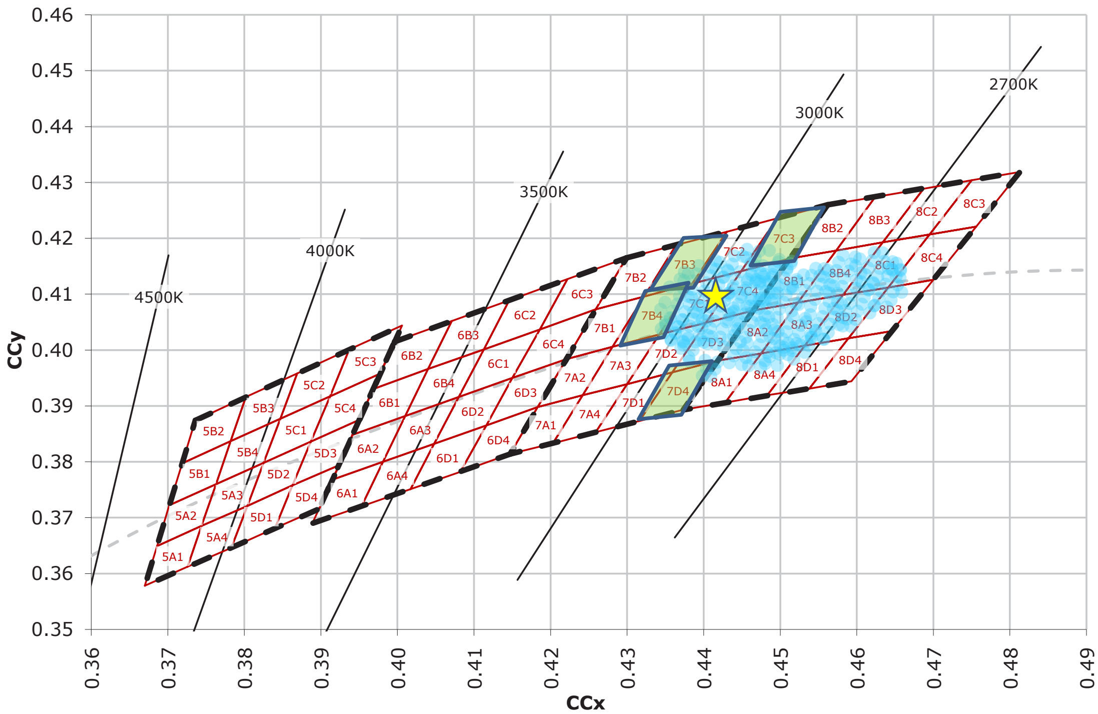


Figure 7: Multi-LED luminaires can use color mixing and spend less on LEDs

Mathematically the results arise because color and flux are additive. LEDs are typically characterized by chromaticity (x, y in the 1931 CIE color space) and flux (Φ = Y).

Tristimulus values, used in color mixing math, can be calculated as follows.

$$X = x*(Y/y)$$

$$Y = Y$$

$$Z = (Y/y)*(1-x-y)$$

The combined color is the result of the added tristimulus values.

$$X_{mix} = X1 + X2 + X3 + X4 \qquad x_{mix} = X_{mix}/(X_{mix} + Y_{mix} + Z_{mix})$$

$$Y_{mix} = Y1 + Y2 + Y3 + Y4 \qquad \text{and} \qquad y_{mix} = Y_{mix}/(X_{mix} + Y_{mix} + Z_{mix})$$

$$Z_{mix} = Z1 + Z2 + Z3 + Z4 \qquad \Phi_{mix} = Y1 + Y2 + Y3 + Y4$$

Of course, there are caveats having to do with luminaire design. One of the following is recommended to obtain the benefits of color mixing.

1. The luminaire should be at a distance from the observer such that the LED light is allowed to “blend” together.

2. Secondary optics should be used to mix and homogenize light from an array of LEDs with slightly different hues.

Examples

This example luminaire can be designed in a number of ways. The light output goal is 2900 K as close to the black body line as possible. A Cree sub-bin that satisfies this colorimetric requirement is 7D3. Assuming the luminaire is a multi-LED device, there are multiple ways to satisfy production requirements.

Solution Using 2 Bins

LED	Bin Codes	x	y	Y(Φ) lm
XP-E #1	8C3 P3	0.4753	0.4263	74
XP-E #2	7A1 Q2	0.4194	0.3866	87

$X_1=x_1*(Y_1/y_1)=82.5057$	$Y_1=74$	$Z_1=(Y_1/y_1)*(1-x_1-y_1)=17.0809$
$X_2=x_2*(Y_2/y_2)=94.3813$	$Y_2=87$	$Z_2=(Y_2/y_2)*(1-x_2-y_2)=43.6575$
$X_{mix}=X_1+X_2=176.8870$	$Y_{mix}=Y_1+Y_2=161$	$Z_{mix}=Z_1+Z_2=60.7384$

$$x_{mix} = X_{mix} / (X_{mix} + Y_{mix} + Z_{mix}) = 0.4437$$

$$y_{mix} = Y_{mix} / (X_{mix} + Y_{mix} + Z_{mix}) = 0.4039$$

$$\Phi = Y_{mix} = 161 \text{ lm}$$

Figure 20: Two XLamp XP-E LEDs warm-white-mixing example

These results fall in the 7D3 bin and are illustrated graphically in Figure 21 below.

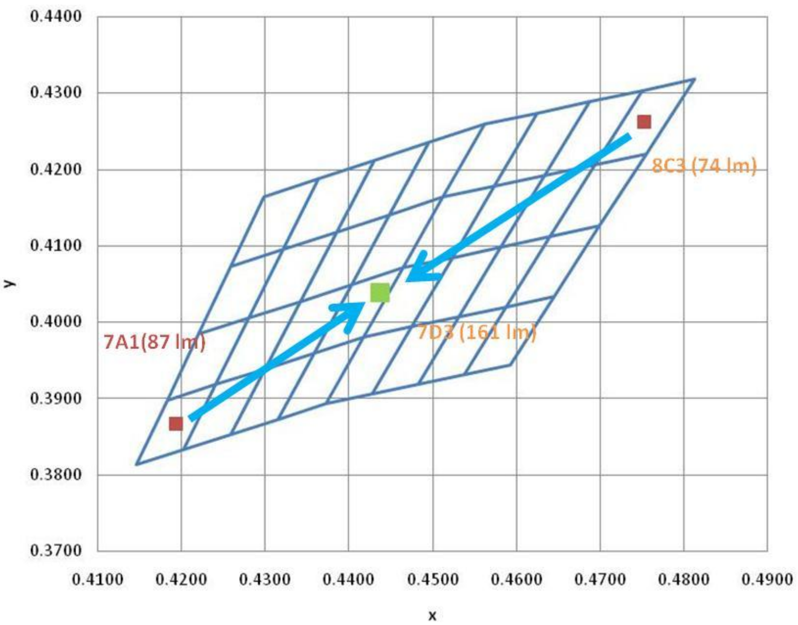


Figure 21: Two LEDs to achieve bin 7D3 @ 161 lumens

Similar calculations can be used to achieve color-mixing results with three and four LEDs as well.

Solution Using 3 Bins

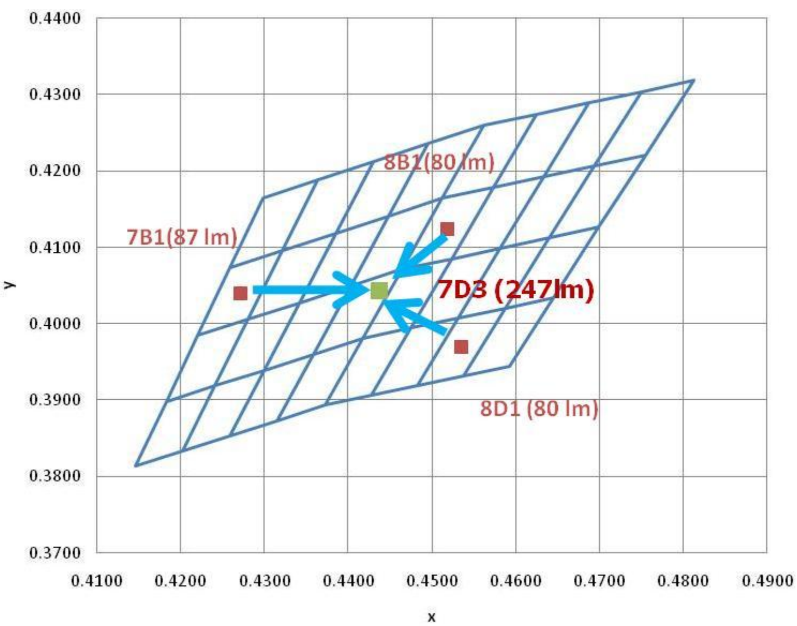


Figure 22: Three LEDs to achieve bin 7D3 @ 247 lumens

Solution Using 4 Bins

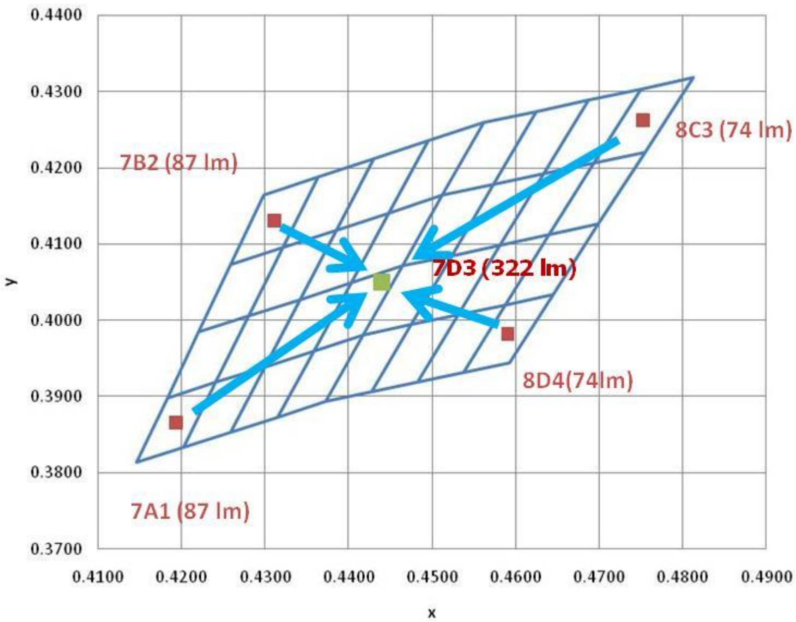


Figure 11: Four LEDs to achieve bin 7D3 @ 322 lumens

For every chromaticity target, there are multiple ways to utilize the entire production distribution to achieve system results that are color consistent and cost effective.

PHOTOMETRIC DEPENDENCIES

LEDs emit light that is characterized by flux and chromaticity. These photometric properties depend on the device materials, forward current through the LED and temperature of the LED junction.

General rules of thumb for white LEDs:

1. As the junction temperature of a device increases, flux decreases and the CCT of that device decreases (shifts toward a warmer color temperature).

2. As the forward drive current of a device increases, flux increases and the CCT of that device increases (shifts toward a cooler color temperature).

CONCLUSION

Just like traditional lamps, LEDs are binned for brightness (lumens) and color (chromaticity). Unlike traditional lighting design, LED color mixing can help multi-LED products take the best advantage of LED performance. LED color mixing is an effective technique to achieve consistent, repeatable, multi-LED luminaires. Color mixing also allows the use of a large chromaticity range while reducing LED unit costs and delivering consistent color point results. Cree's EasyWhite LEDs help simplify luminaire design by mixing colors within the LED component.