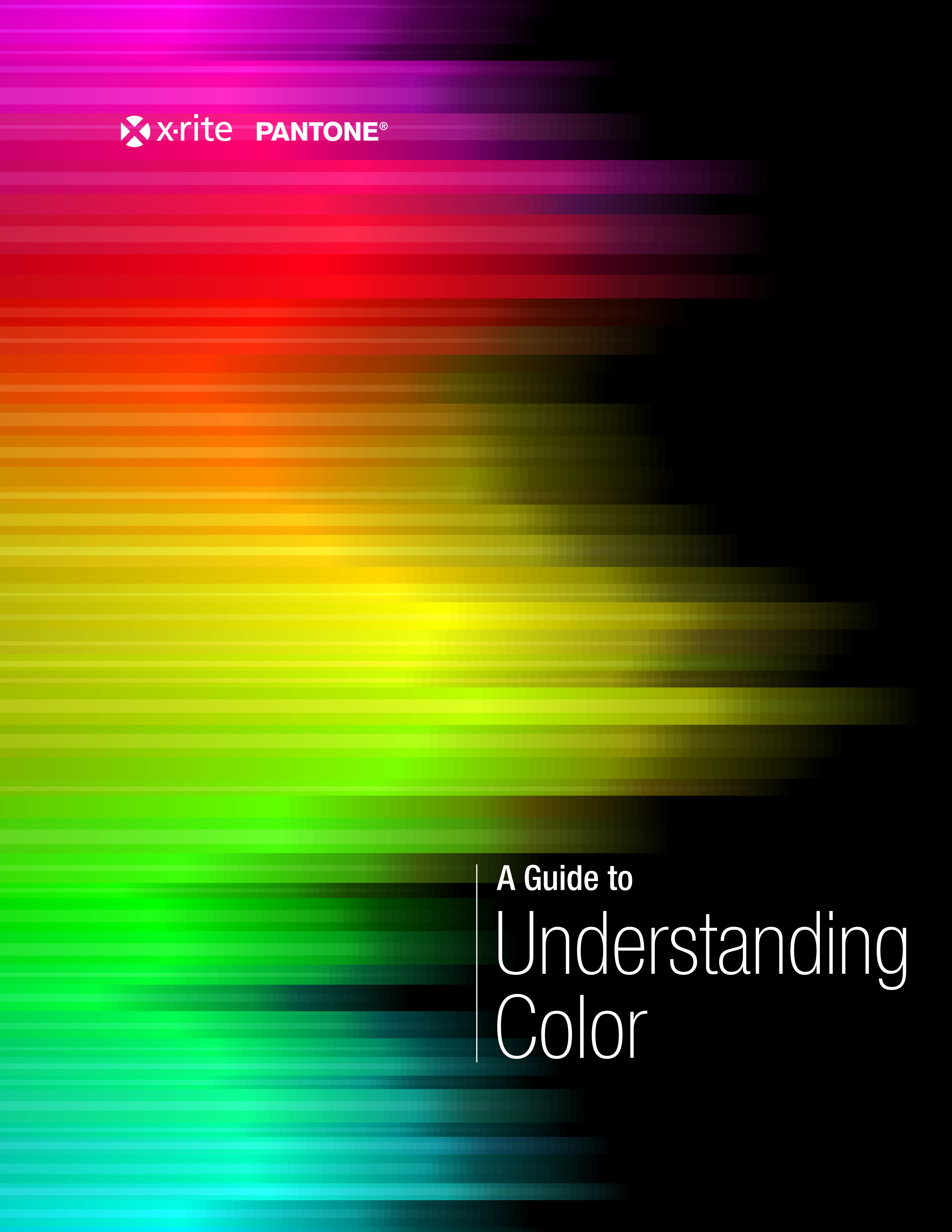

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A Guide to Understanding Color

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Color Your Business Successful

How important is color to your business, or more specifically, how important is accurate color? When products reach the shelf, do they attract attention? Do they inspire confidence? Do they ensure immediate brand recognition?

Color is a factor in answering all of these questions. Studies show that 70% of the buying decision is made at the shelf, and consumers will reach past a package that looks faded to get a “fresher” one with brighter colors.

This Guide to Understanding Color is a handy educational tool and how-to guide for all things color. Whether you are a novice or an expert in the art and science of color, you will find useful information here that will help you ensure that color plays a positive role in the success of the products you are manufacturing and recognition of their respective brands, especially at the Zero Moment of Truth when the buying decision is made.

We’ll talk about the basics of color, how best to measure, manage, communicate and report on color, and proactive approaches to ensuring consistent and reliable color, in even the most complex of workflows and supply chains.

With all of the recent advances in color measurement instruments and software, ensuring that color complies with specifications and is within acceptable tolerances is easier than ever before. We hope you will find this Guide useful in coloring your business even more successful!

Table of Contents

Communicating Color

In any discussion of color, a great place to start is with the challenges we face in communicating color.

Here is an example that demonstrates color communication challenges. How would you describe the color of this rose? Would you say it's yellow, sort of lemon yellow or maybe a bright canary yellow? Ask the same question of a couple of your colleagues and compare notes.

The perception and interpretation of color is highly subjective. Eye fatigue, age, the environment in which you are viewing the color and other factors can influence color perception.

But even without such physical considerations, each observer interprets color based on personal preferences. Each person also verbally defines an object's color differently. As a result, objectively communicating a particular color to another person without using some type of standard is difficult. There also must be a way to compare one color to the next with accuracy.

The solution to this conundrum is a measurement instrument that explicitly identifies the color being measured; that is, an instrument that differentiates one color from all others and assigns it a numeric value.

KEY TAKEAWAY

The perception of color is highly subjective and can be influenced by a number of physiological, experiential and environmental factors. A measurement instrument that assigns a number to a specific color is the most reliable means of accurately communicating that color with others.

The Science of Color

In this section of the guide, we delve into the science of color in detail. As you might expect, it is a fairly technical discussion. However, it is a good reference for anyone, in any industry, involved with the specification, communication, measurement, management and reporting of color. Please refer to the final chapter of this guide, Right the First Time, Right Every Time: An Exceptional Color Workflow, which brings together all of the knowledge contained in this guide in an explanation of how color can be efficiently and effectively managed across even the most complex supply chain.

Attributes of Color

Each color has its own distinct appearance, based on three elements: hue, chroma (or saturation) and value (lightness). By describing a color using these three attributes, you can accurately identify a particular color and distinguish it from any other.

Hue

When asked to identify the color of an object, you'll most likely speak first of its hue. Quite simply, hue is how we perceive an object's color — red, orange, green, blue, etc. The color wheel in Figure 7 shows the continuum of color from one hue to the next. As the wheel illustrates, if you were to mix blue and green paints, you would get blue-green. Mix blue and yellow to get green, red and yellow for orange, or add yellow to green for yellow-green, and so on.

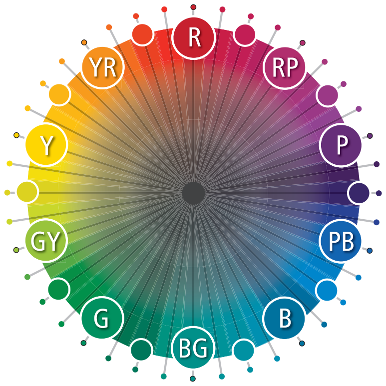


Figure 7. Hue

Chroma

Chroma describes the vividness or dullness of a color — in other words, how close the color is to either gray or the pure hue. For example, think of the appearance of a tomato and a radish. The red of the tomato is vivid, while the radish appears duller.

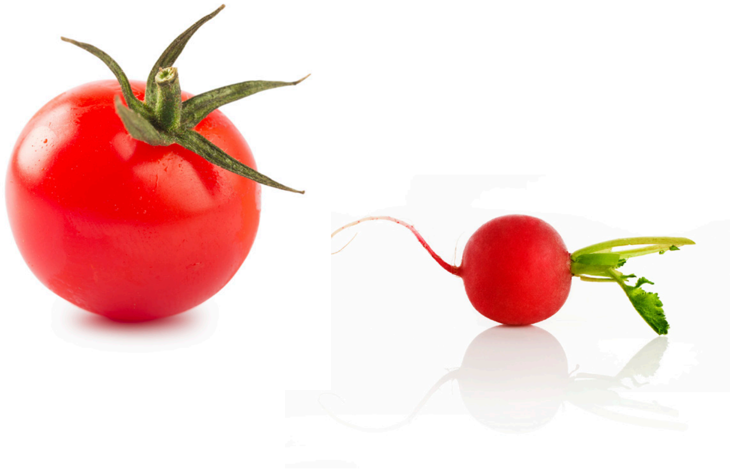


Figure 8 shows how chroma changes as we move from the center to the perimeter. Colors in the center are gray (dull) and become more saturated (vivid) as they move toward the perimeter. Chroma is also known as saturation.

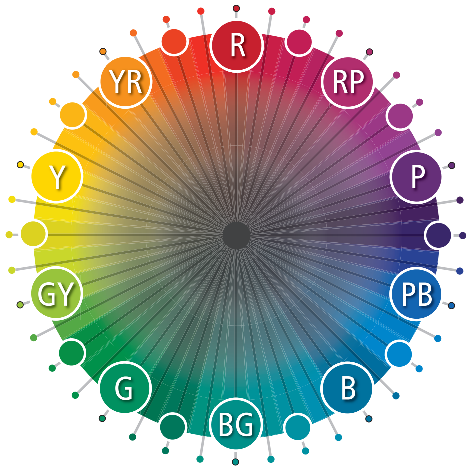
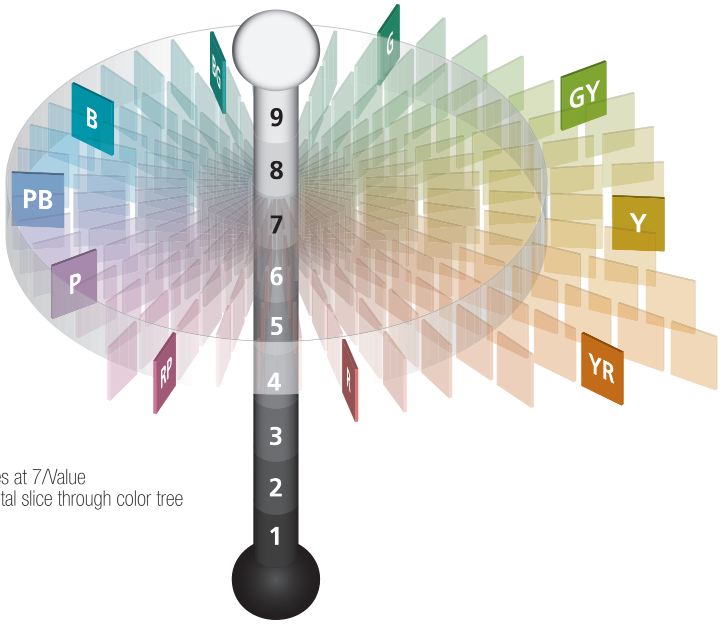


Figure 8. Chromaticity

Value

The luminous intensity of a color — i.e., its degree of lightness — is called its value. Colors can be classified as light or dark when comparing their value.

For example, when a tomato and a radish are placed side by side, the red of the tomato appears to be much lighter. In contrast, the radish has a darker red value. In Figure 9, the value, or lightness, characteristic is represented on the vertical axis.



VALUE
10 Hues at 7/Value
Horizontal slice through color tree

Figure 9. Three-dimensional color system depicting lightness

Scales for Measuring Color

As we referenced earlier, the key to accurately and concisely communicating color is "color by the numbers." In this section, we will discuss several ways in which those "numbers" can be calculated to represent individual colors.

The Munsell Scale

In 1905, artist Albert H. Munsell originated a color ordering system — or color scale — which is still used today. The Munsell System of Color Notation is significant from a historical perspective because it's based on human perception. Moreover, it was devised before instrumentation was available for measuring and specifying color. The Munsell System assigns numerical values to the three properties of color: hue, chroma and value. Adjacent color samples represent equal intervals of visual perception.

The model in Figure 10 depicts the Munsell Color Tree, which provides physical samples for judging visual color.

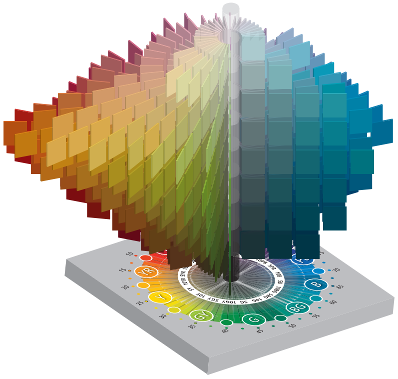
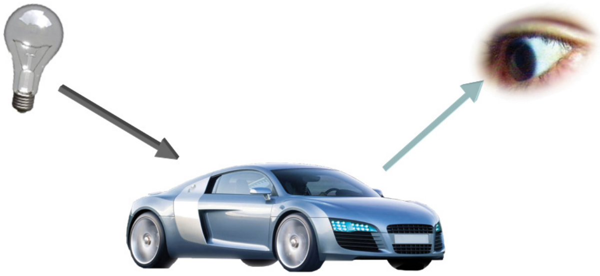


Figure 10. Munsell Color Tree

As we examine how color occurs, there are three things that must be present:

- A light source (illuminant)
- An object (sample)
- An observer/processor

We as humans see color because our eyes process the interaction of light hitting an object. What if we replace our eyes with an instrument —can it see and record the same color differences that our eyes detect?



CIE Color Systems

The CIE, or Commission Internationale de l'Eclairage (translated as the International Commission on Illumination), is the body responsible for international recommendations for photometry and colorimetry. In 1931, the CIE standardized color order systems by specifying the light source (or illuminants), the observer and the methodology used to derive values for describing color, regardless of industry or use case.

The CIE Color Systems utilize three coordinates to locate a color in a color space. These color spaces include:

- CIE XYZ
- CIE L*a*b*
- CIE L*C*h°

To obtain these values, we must understand how they are calculated. As stated earlier, our eyes need three things to see color: a light source, an object and an observer/processor. The same is true for instruments to see color. Color measurement instruments perceive color the same way our eyes do — by gathering and filtering the wavelengths of light reflected from an object. The instrument perceives the reflected light wavelengths as numeric values. These values are recorded as points across the visible spectrum and are called spectral data. Spectral data is represented as a spectral curve. This curve is the color's fingerprint (Figure 11).

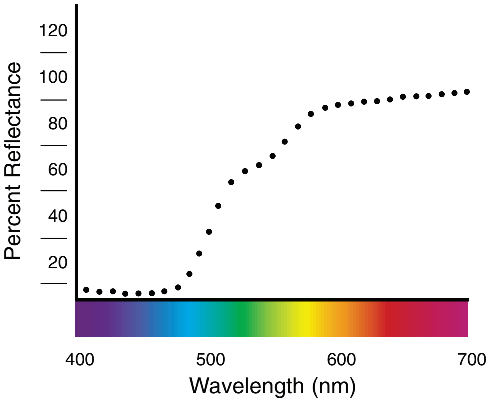


Figure 11. Spectral curve from a measured sample

A spectrophotometer measures spectral data – the amount of light energy reflected from an object at several intervals along the visible spectrum. The spectral data is shown as a spectral curve.

Once we obtain a colors spectral, or reflectance curve, we can apply mathematics to map the color onto a color space.

To do this, we multiply the reflectance curve data by a CIE standard illuminant. The illuminant is a graphical representation of the light source under which the samples are viewed. Each light source has a power distribution that affects how we see color. Examples of different illuminants are

- A — incandescent,
- D65 — daylight (Figure 12) and
- F2 — fluorescent.

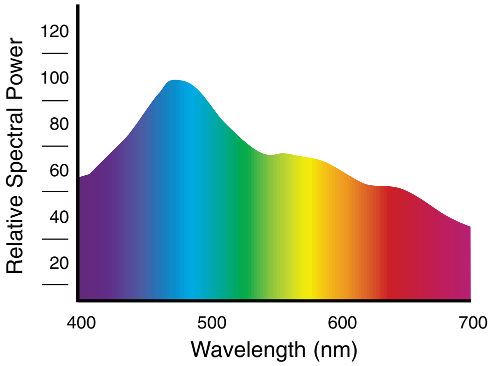


Figure 12. Daylight (Standard Illuminant D65/10°)

We multiply the result of this calculation by the CIE standard observer.

The CIE commissioned work in 1931 and 1964 to derive the concept of a standard observer, which is based on the average human response to wavelengths of light (Figure 13). In short, the standard observer represents how an average person sees color across the visible spectrum.

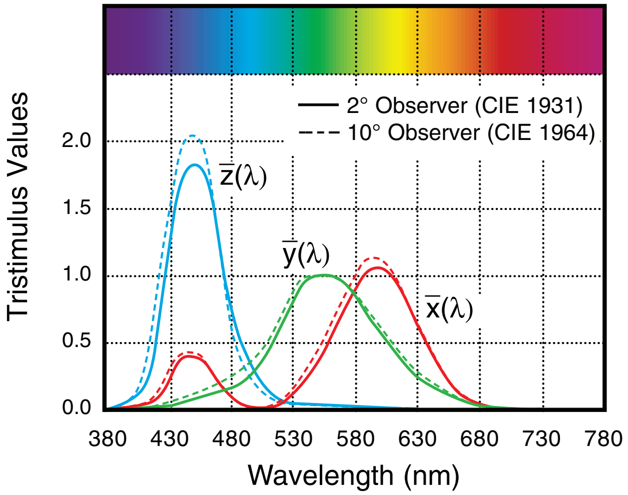
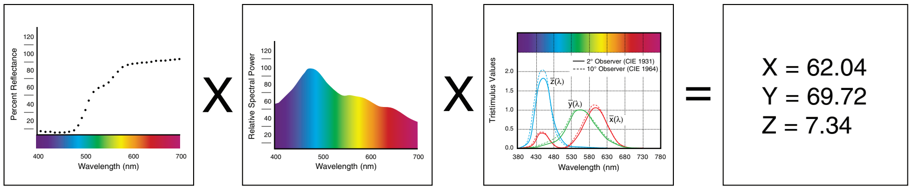


Figure 13. CIE 2° and 10° Standard Observers

Once these values are calculated, we convert the data into the tristimulus values of XYZ (Figure 14). These values can now identify a color numerically.



Spectral Curve D65 Illuminant Standard Observer Tristimulus Values

Figure 14. Tristimulus values

Chromaticity Values

Tristimulus values, unfortunately, have limited use as color specifications because they correlate poorly with visual attributes. While Y relates to value (lightness), X and Z do not correlate to hue and chroma.

As a result, when the 1931 CIE standard observer was established, the commission recommended using the chromaticity coordinates xyz. These coordinates are used to form the chromaticity diagram in Figure 15. The notation Yxy specifies colors by identifying value (Y) and the color as viewed in the chromaticity diagram (x,y).

As Figure 16 shows, hue is represented at all points around the perimeter of the chromaticity diagram. Chroma, or saturation, is represented by a movement from the central white (neutral) area out toward the diagram's perimeter, where 100% saturation equals pure hue.

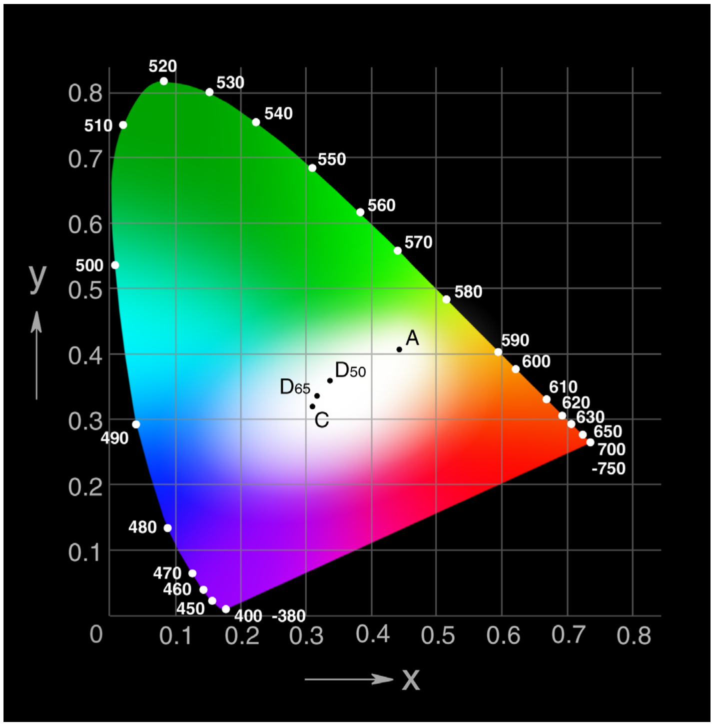


Figure 15. CIE 1931 (x,y) chromaticity diagram

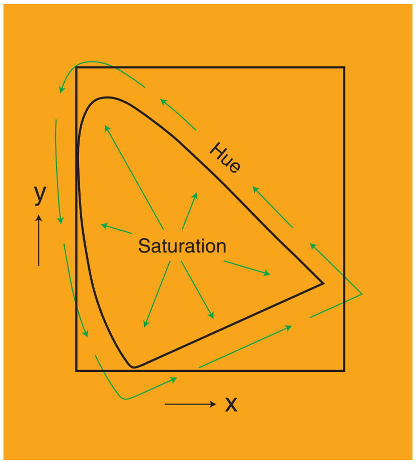


Figure 16. Chromaticity diagram

Expressing Colors Numerically

To overcome the limitations of chromaticity diagrams like Yxy, the CIE recommended two alternate, uniform color scales: CIE 1976 (L*a*b*) or CIELAB, and CIELCH (L*C*h°).

These color scales are based on the opponent-colors theory of color vision, which says that two colors cannot be both green and red at the same time, nor blue and yellow at the same time. As a result, single values can be used to describe the red/green and the yellow/blue attributes.

CIELAB (L*a*b*)

When a color is expressed in CIELAB, L* defines lightness, a* denotes the red/green value and b* the yellow/blue value.

Figures 17 and 18 (on the following page) show the color-plotting diagrams for L*a*b*. The a* axis runs from left to right. A color measurement movement in the +a direction depicts a shift toward red. Along the b* axis, +b movement represents a shift toward yellow. The center L* axis shows L = 0 (black or total absorption) at the bottom. At the center of this plane is neutral or gray.

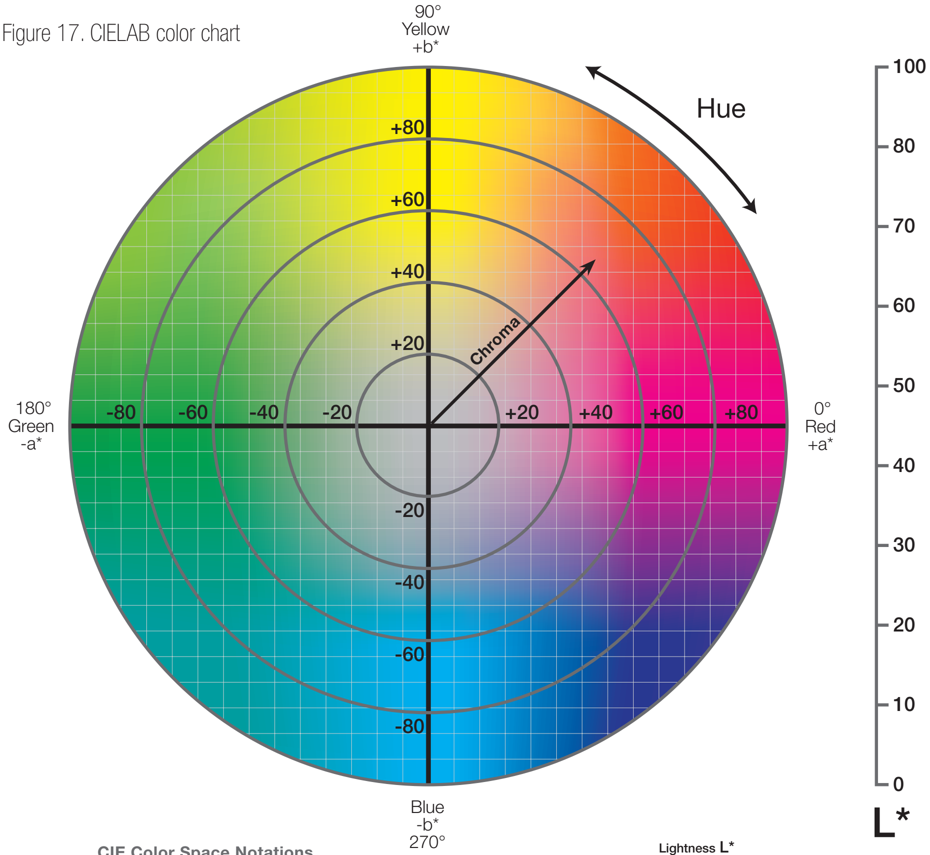
To demonstrate how the L*a*b* values represent the specific colors of Flowers A and B, we've plotted their values on the CIELAB Color Chart in Figure 17.

Flower A:
L* = 52.99 a*= 8.88 b*= 54.53

Flower B:
L* = 29.00 a*= 52.48 b*= 22.23

The a* and b* values for Flowers A and B intersect at color spaces identified respectively as points A and B (see Figure 17). These points specify each flower's hue (color) and chroma (vividness/dullness). When their L* values (degree of lightness) are added in Figure 18, the final color of each flower is obtained.

Figure 17. CIELAB color chart



CIE Color Space Notations

ΔL^* -	difference in lightness/darkness value	"+" = lighter "–" = darker
Δa^* -	difference on red/green axis	"+" = redder "–" = greener
Δb^* -	difference on yellow/blue axis	"+" = yellower "–" = bluer
ΔC^* -	difference in chroma	"+" = brighter "–" = duller
ΔH^* -	difference in hue	
ΔE^* -	total color difference value	
ΔE_{CMC} -	total acceptable color difference value	

ΔE_H 1942 • ΔE^*_{ab} 1976 • ΔE_{CMC} 1984 • ΔE_{94} 1992 • ΔE_{00} 2000

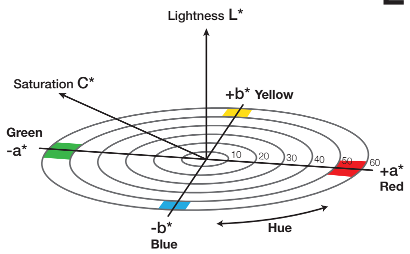


Figure 18. The L* value is represented on the center axis. The a* and b* axes

CIELCH (L*C*h°)

While CIELAB uses Cartesian coordinates to calculate a color in a color space, CIELCH uses polar coordinates. This color expression can be derived from CIELAB. The L* defines lightness, C* specifies chroma and h° denotes hue angle, an angular measurement.

The L*C*h° expression offers an advantage over CIELAB in that it is very easy to relate to the earlier systems that are based on physical samples, like the Munsell Color Scale.

$L^* = 116\ (Y/Yn)1/3 - 16$
$a^* = 500\ [(X/Xn)1/3 - (Y/Yn)1/3]$
$b^* = 200\ [(Y/Yn)1/3 - (Z/Zn)1/3]$
$L^* = 116\ (Y/Yn)1/3 - 16$
$C^* = (a2 + b2)1/2$
$h^\circ = \arctan (b^*/a^*)$

Xn, Yn, Zn, are values for a reference white for the illumination/observer used.

Color Differences, Notation and Tolerancing
Delta CIELAB and CIELCH

Assessment of color is more than a numeric expression. Usually it’s an assessment of the color difference (delta) from a known standard. CIELAB and CIELCH are used to compare the colors of two objects.

The expressions for these color differences are ΔL* Δa* Δb* or DL* Da* Db*, and ΔL* ΔC* ΔH* or DL* DC* DH* (Δ or D symbolizes “delta,” which indicates difference).
Given ΔL* Δa* Δb*, the total difference or distance on the CIELAB diagram can be stated as a single value, known as ΔE*.
$\Delta E^{*}ab = [(\Delta L2) + (\Delta a2) + (\Delta b2)]1/2$

Let’s compare the color of Flower A to Flower C, pictured on the following page. Separately, each would be classified as a yellow rose. But what is their relationship when set side by side? How do the colors differ?

Using the equation for ΔL* Δa* Δb*, the color difference between Flower A and Flower C can be expressed as:
$\Delta L^{*} = +11.10$
$\Delta a^{*} = -6.10$
$\Delta b^{*} = -5.25$

The total color difference can be expressed as ΔE*=13.71.

Flower A:
$L^* = 52.99$ $a^*= 8.882$ $b^*= 54.53$

Flower C:
$L^* = 64.09$ $a^*= 2.72$ $b^*= 49.28$

$$\Delta L^* = +11.10,\ \Delta a^* = -6.10,\ \Delta b^* = -5.25$$
$$\Delta E^*ab = [(+\ 11.1)2 + (-6.1)2 + (-5.25)2]1/2$$
$$\Delta E^*ab = 13.71$$

The values for Flowers A and C are shown above. On the a* axis, a reading of –6.10 indicates greener or less red. On the b* axis, a reading of –5.25 indicates bluer or less yellow. On the L* plane, the measurement difference of +11.10 shows that Flower C is lighter than Flower A.

If the same two flowers were compared using CIELCH, the color differences would be expressed as:

$\Delta L^* = +11.10$
$\Delta C^* = -5.88$
$\Delta H^* = 5.49$

Referring again to the flowers shown above, the ΔC* value of –5.88 indicates that Flower C is less chromatic, or less saturated. The ΔH* value of 5.49 indicates that Flower C is greener in hue than Flower A. The L* and ΔL* values are identical for CIELCH and CIELAB.

CIE Color Space Notation

ΔL^* = difference in lightness/darkness value
+ = lighter − = darker
Δa^* = difference on red/green axis
+ = redder − = greener
Δb^* = difference on yellow/blue axis
+ = yellower − = bluer
ΔC^* = difference in chroma
+ = brighter − = duller
ΔH^* = difference in hue
ΔE^* = total color difference value

Refer to Figure 17 above.

Visual Color and Tolerancing

Poor color memory, eye fatigue, color blindness and viewing conditions can all affect the human eye's ability to distinguish color differences. In addition to those limitations, the eye does not detect differences in hue (red, yellow, green, blue, etc.), chroma (saturation) or lightness equally. In fact, the average observer will see hue differences first, chroma differences second and lightness differences last. Visual acceptability is best represented by an ellipsoid (Figure 19).

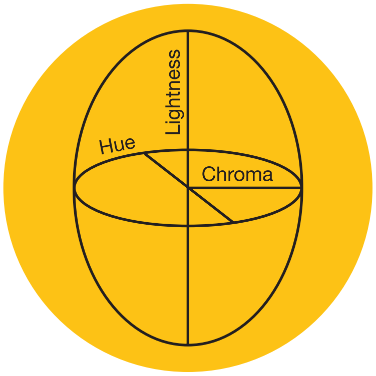


Figure 19. Tolerance ellipsoid

As a result, our tolerance for an acceptable color match consists of a three-dimensional boundary with varying limits for lightness, hue and chroma, and must agree with visual assessment. CIELAB and CIELCH can be used to create those boundaries. Additional tolerancing formulas, known as CMC and CIE94, produce ellipsoidal tolerances.

CIELAB Tolerancing

When tolerancing with CIELAB, you must choose a difference limit for ΔL^* (lightness), Δa^* (red/green), and Δb^* (yellow/blue). These limits create a rectangular tolerance box around the standard (Figure 20).

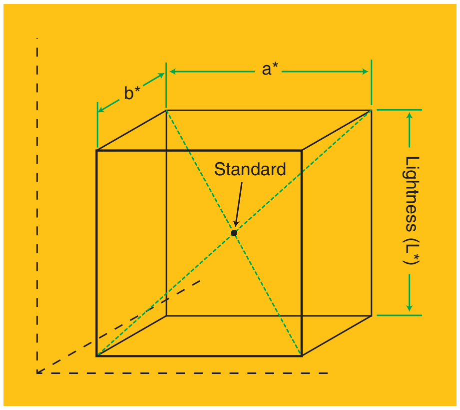


Figure 20. CIELAB tolerance box

When comparing this tolerance box with the visually accepted ellipsoid, some problems emerge. A box-shaped tolerance around the ellipsoid can give good numbers for unacceptable color. If the tolerance box is made small enough to fit within the ellipsoid, it is possible to get bad numbers for visually acceptable color (Figure 21).

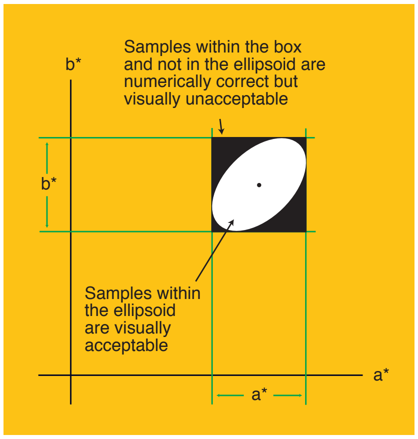


Figure 21. Numerically correct versus visually acceptable

CIELCH Tolerancing

CIELCH users must choose a difference limit for ΔL* (lightness), ΔC* (chroma) and ΔH* (hue). This creates a wedge-shaped box around the standard. Since CIELCH is a polar-coordinate system, the tolerance box can be rotated in orientation to the hue angle (Figure 22).

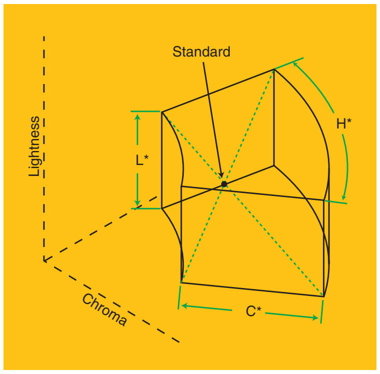


Figure 22. CIELCH tolerance wedge

When this tolerance is compared with the ellipsoid, we can see that it more closely matches human perception. This reduces the amount of disagreement between the observer and the instrumental values (Figure 23).

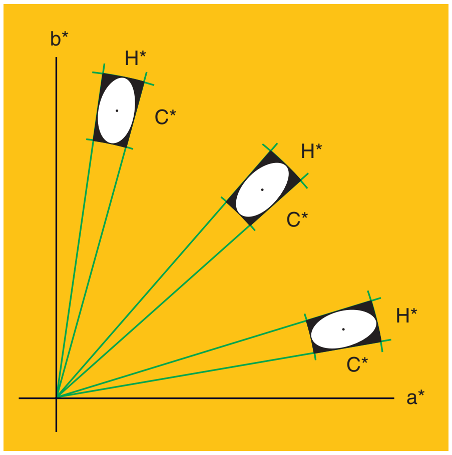


Figure 23. CIELCH tollerance ellipsoids

CMC Tolerancing

CMC is not a color space but rather a tolerancing system. CMC tolerancing is based on CIELCH and provides better agreement between visual assessment and measured color difference. CMC tolerancing was developed by the Colour Measurement Committee of the Society of Dyers and Colourists in Great Britain and became public domain in 1988.

The CMC calculation mathematically defines an ellipsoid around the standard color with semi-axis corresponding to hue, chroma and lightness. The ellipsoid represents the volume of acceptable color and automatically varies in size and shape depending on the position of the color in color space.

Figure 24 shows the variation of the ellipsoids throughout color space. The ellipsoids in the orange area of color space are longer and narrower than the broader and rounder ones in the green area. The size and shape of the ellipsoids also change as the color varies in chroma and/or lightness

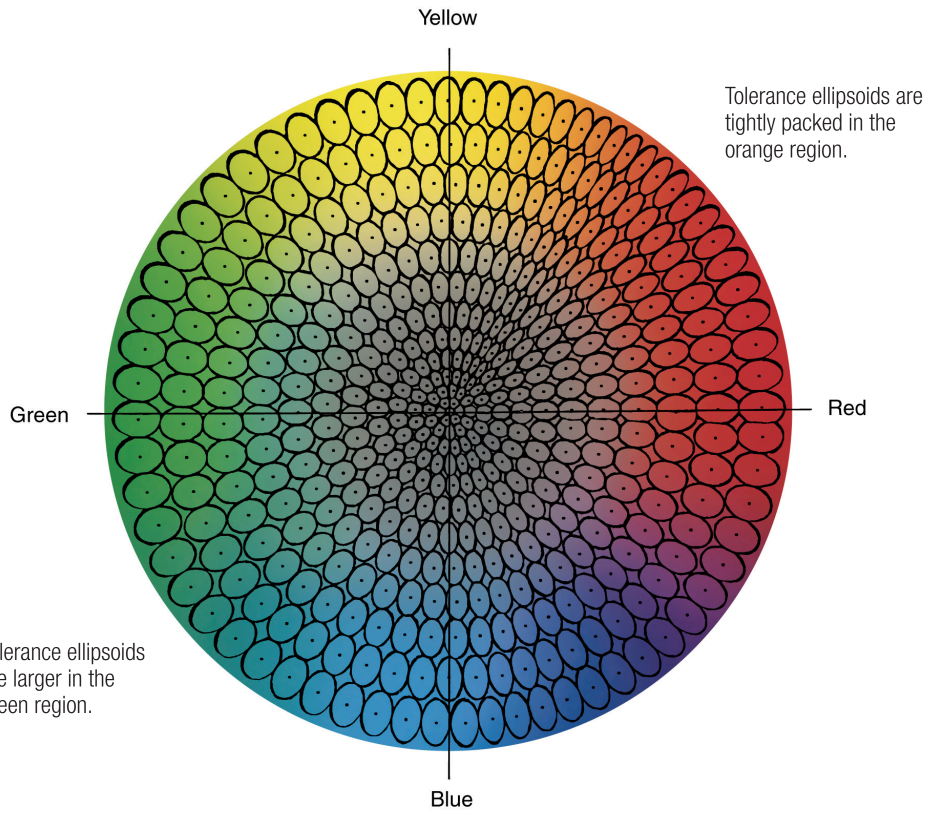


Figure 24. Tolerance ellipsoids in color space

The CMC equation allows you to vary the overall size of the ellipsoid to better match what is visually acceptable. By varying the commercial factor (cf), the ellipsoid can be made as large or small as necessary to match visual assessment. The cf value is the tolerance, which means that if cf=1.0, then ΔE CMC less than 1.0 would pass, but more than 1.0 would fail (see Figure 25).

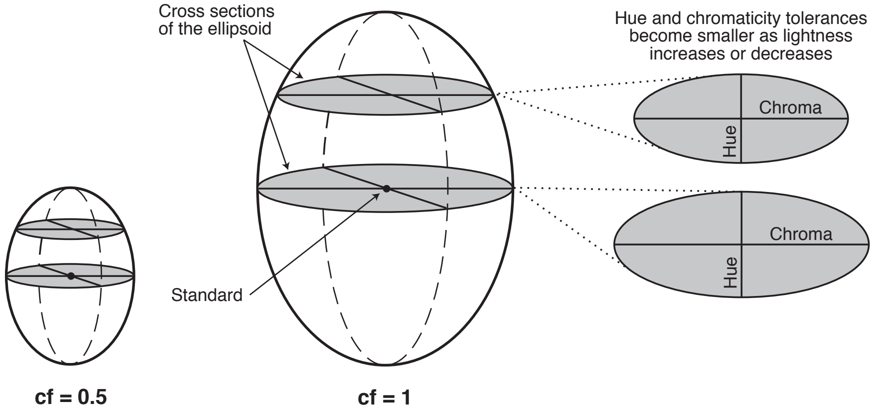


Figure 25. Commercial factor (cf) of tolerances

Since the eye will generally accept larger differences in lightness (l) than in chroma (c), a default ratio for (l:c) is 2:1. A 2:1 ratio will allow twice as much difference in lightness as in chroma. The CMC equation allows this ratio to be adjusted to achieve better agreement with visual assessment (see Figure 26).

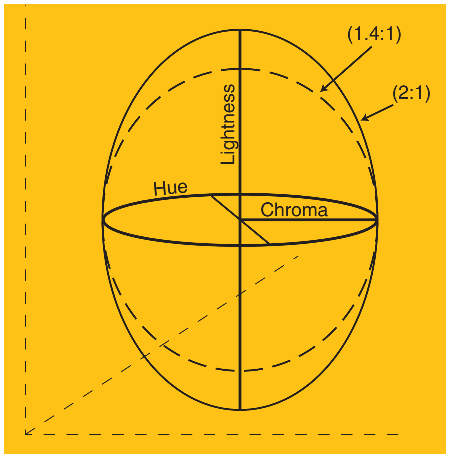


Figure 26. CMC tolerance ellipsoids

CIE94 Tolerancing

In 1994, the CIE released a new tolerance method called CIE94. Like CMC, the CIE94 tolerancing method also produces an ellipsoid. The user has control of the lightness (kL) to chroma (Kc) ratio, as well as the commercial factor (cf). These settings affect the size and shape of the ellipsoid in a manner similar to how the l:c and cf settings affect CMC.

However, while CMC is targeted for use in the textile industry, CIE94 is targeted for use in the paint and coatings industry. You should consider the type of surface being measured when choosing between these two tolerances.

If the surface is textured or irregular, CMC may be the best fit. If the surface is smooth and regular, CIE94 may be the best choice.

Delta E 2000

Delta E 2000 is the first major revision of the delta E equation since CIE94 (or dE94). Unlike dE94, which assumes that L* correctly reflects the perceived differences in lightness, dE2000 varies the weighting of L* depending on where in the lightness range the color falls. dE2000 is becoming increasingly popular in graphic arts applications and will likely replace dE94 across the board in the not-too-distant future.

Visual Assessment vs. Instrumental

Though no color tolerancing system is perfect, the CMC, CIE94, and now, dE2000 equations best represent color differences as our eyes see them.

Tolerance Method	% Agreement with Visual
CIELAB	75%
CIELCH	85%
CMC or CIE 94	95%

Choosing the Right Tolerance
When deciding which color difference calculation to use, consider the following five rules :

1. Select a single method of calculation and use it consistently.
2. Always specify exactly how the calculations are made.
3. Never attempt to convert between color differences calculated by different equations through the use of average factors.
4. Use calculated color differences only as a first approximation in setting tolerances, until they can be confirmed by visual judgments.
5. Always remember that nobody accepts or rejects color because of numbers — it is the way it looks that counts, especially when consumers are making buying decisions at the shelf or in the showroom.

---

[1] Billmeyer, Fred and Max Saltzman, Principles of Color Technology, Wiley, 2nd edition, May 1981

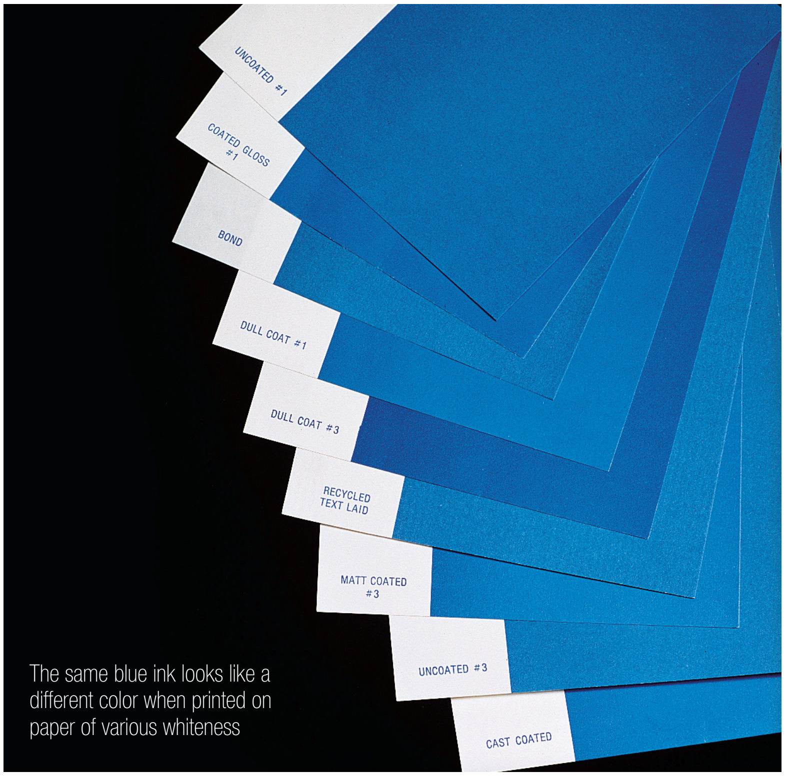
Other Color Expressions

White and Yellow Indices

Certain industries, such as paint, textiles and paper manufacturing, evaluate their materials and products based on standards of whiteness. Typically, this whiteness index is a preference rating for how white a material should appear, be it photographic and printing paper or plastics.

In some instances, a manufacturer may want to judge the yellowness or tint of a material. This is done to determine how much that object's color departs from a preferred white toward a bluish tint.

The effect of whiteness or yellowness can be significant, for example, when printing inks or dyes on paper. A blue ink printed on a highly-rated white stock will look different than the same ink printed on newsprint or another low-rated stock.



The same blue ink looks like a different color when printed on paper of various whiteness

The American Standards Test Methods (ASTM) has defined whiteness and yellowness indices. The E313 whiteness index is used for measuring near-white, opaque materials such as paper, paint and plastic. In fact, this index can be used for any material whose color appears white.

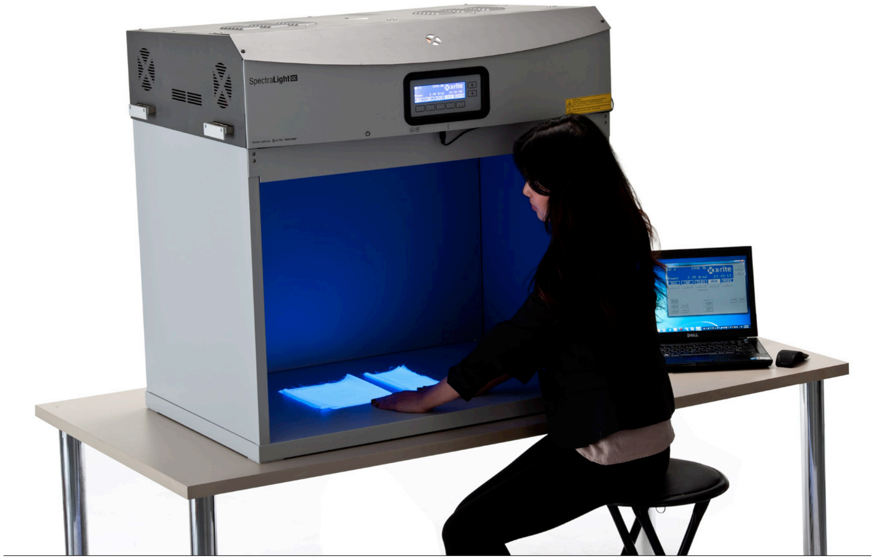
The ASTM's E313 yellowness index is used to determine the degree to which a sample's color shifts away from an ideal white. The D1925 yellowness index is used for measuring plastics.

Optical Brightening Agents

Companies are increasingly using optical brightening agents (OBAs), also referred to as Fluorescent Whitening Agents (FWAs), to achieve a "whiter-than-white" effect on a range of materials. Adding these optical brighteners gives products a brighter, whiter appearance and compensates for the yellowing that can happen with white products over time.

Adding OBAs obviously makes for a brighter product, but the addition of these brighteners fundamentally alters the way the color is seen, which has made it impossible to accurately measure color using conventional measurement techniques.

However, under an ultraviolet light source, such as a "black" light, you can clearly detect visible color differences in products that contain various amounts of OBAs. Products that contain more OBAs will appear lighter, while products with less OBAs will be darker. The challenge is that you need to have a consistent amount of UV light to be able to quantify the amount of OBAs in a given product. This means that when there is little or no UV light, the color differences may be invisible. But when UV light is present, the color differences become quite visible. So while materials and fabrics that use OBAs may appear similar in production, those same products may look much different under varied lighting conditions, such a retail store, daylight, or household light.



The only way to bring color consistency to products that use OBAs is with tools that accurately measure the amount of OBAs in the product. To do that, X-Rite Pantone brought calibrated UV light control to sphere benchtop and portable spectrophotometers, including the Ci7800/Ci7600 benchtops and the Ci64UV handheld. These devices deliver calibrated UV light that enables the measurement of OBAs. Optically brightened items can also be visually examined under controlled UV lighting such as that provided by the X-Rite SpectraLight QC light booth.

CxF3

In 2015, the ISO TC130 committee that sets global standards for the Graphic Arts adopted the X-Rite Color Exchange Format version 3 (CxF3) as the new standard for color data exchange and verification. This standard (ISO 17972-1:2015) provides the graphic arts industry with an accurate, efficient way to communicate color information across any supply chain.

The CxF3 format is defined in a completely open way so that all aspects of a color can be communicated, even when the application and the color communication features required are unknown. This means that every software vendor implementing and supporting CxF3 is able to easily and accurately extend the information throughout global workflows.

Measuring Color by the Numbers

The most commonly used instruments for measuring color are spectrophotometers. For some applications, colorimeters can also be used; these will be discussed later in this guide. You can also refer to the glossary as you read through the rest of this guide if you run across terms that are not familiar.

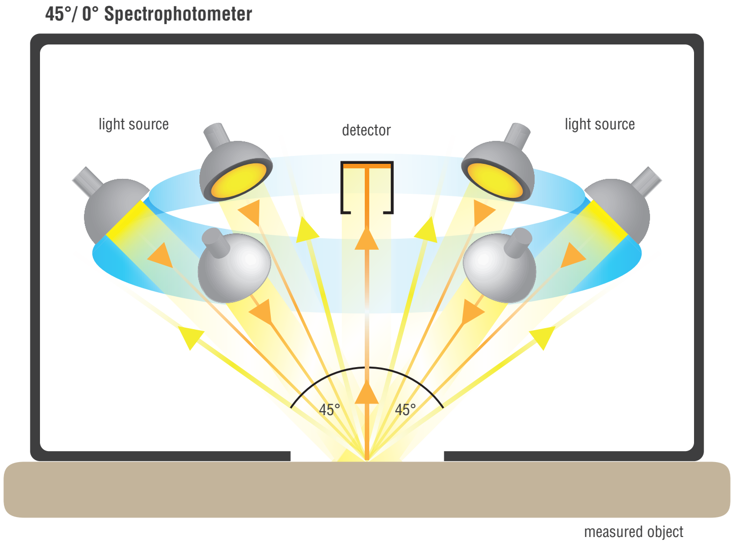
There are three primary types of spectrophotometers used for print, packaging and industrial applications today: traditional 0°/45° (or 45°/0°) spectrophotometers, sphere (or diffuse/8°) spectrophotometers and multi-angle (MA) spectrophotometers.

These instruments primarily capture color information, and in some cases are able to capture appearance data such as gloss. In the future, expect instruments to arrive on the market that can accurately capture both color and appearance for a more complete data set describing the object or material being measured. First, let's look at what the names mean.

45°/0° spectrophotometers

In the case of 45°/0° spectrophotometers, the first number refers to the angle of illumination and the second number refers to the viewing angle (This is true regardless of the geometry of the instrument – the first number always defines illumination, and the second always defines viewing). With a 45°/0° spectrophotometer such as the X-Rite VS450, the light source shines at 45° from the perpendicular of the sample being measured, and the detector receives reflected light at a 0° angle, or perpendicular to the surface of the object.

VS450 45°/0° spectrophotometer



The geometry associated with 45°/0° spectrophotometers.

Sphere Spectrophotometers

With a sphere (or diffuse/8°) spectrophotometer such as the X-Rite Ci64, the object to be measured is illuminated diffusely, or from all directions, and the detector receives the reflected light at an 8° angle from the surface of the measured object. This is known as "sphere geometry" because these instruments contain a sphere providing diffuse illumination.

X-Rite Ci64 Portable Sphere Spectrometer

In a sphere spectrophotometer, the inside of the sphere is lined with a highly reflective, low gloss, matte white substance used to project and diffuse the light, making it a near perfect white reflector. As the light beam strikes a point on the surface of the sphere, more than 99% of the light is reflected. At the same time, the matte finish of the sphere causes the light to be scattered randomly in all directions. This happens at every point on the surface and effectively causes light inside the sphere to seem to come from every direction at once: the inside of the sphere thus becomes the light source. Figure 5 shows the geometry associated with a sphere spectrophotometer.

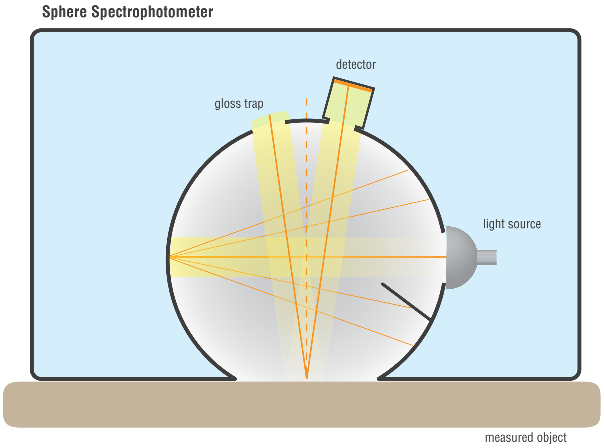


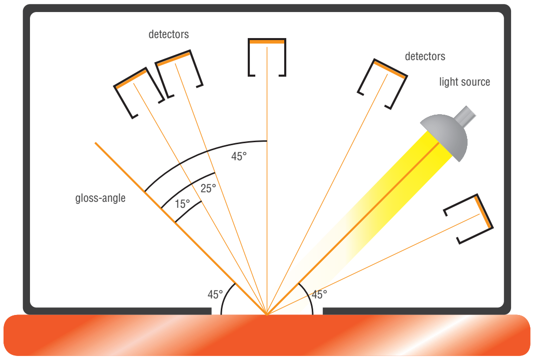
Figure 5. Diffuse Geometry for Sphere (Diffuse/8°) Spectrophotometers

KEY TAKEAWAY

Spectrophotometers come in three flavors: Multi-Angle (MA), 45°/0° and Spherical. Each addresses different color measurement needs.

Multi-Angle (MA) Spectrophotometers

MA spectrophotometers are best suited for measurements of industrial production applications involving special effect surfaces, such as automotive coatings, metallic or pearlescent inks or coatings, and cosmetics. These are typically used in the lab, on the production line, in QC operations and in the shipping area. MA spectrophotometers, such as the X-Rite MA98 Portable Multi-Angle Spectrophotometer, are quite complex and require users to verify five or more sets of L*a*b* values or delta E (dE) values. They typically have an aperture size of 12mm, which is too large for measuring the fine detail that occurs in many small scale industrial applications. Primary illumination is provided at a 45° angle. Some models have secondary illumination at a 15° angle.



Multi-Angle Spectrophotometer.

An application example for an MA spectrophotometer lies in the use of non-contact multi-angle spectrophotometers for collecting colorimetric data on special effects coatings in the automotive industry, capturing reliable color data in cases where special effect coatings are used.

Colorimeters

Colorimeters are not the same as spectrophotometers. Colorimeters are tristimulus (three-filtered) devices that make use of red, green, and blue filters that emulate the response of the human eye to light and color. In some quality control applications, these tools represent the lowest cost answer. Blended instruments, called spectrocolorimeters, incorporate colorimeter functionality with some functionality of a spectrophotometer.

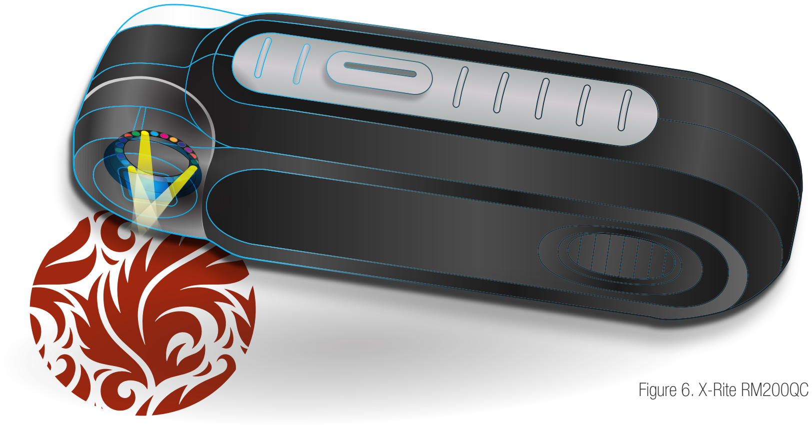


Figure 6. X-Rite RM200QC Colorimeter

Colorimeters cannot compensate for metamerism (a shift in the appearance of a sample due to the light used to illuminate the surface). Since colorimeters only use a single type of light and because they do not record the spectral reflectance of the media, they cannot predict this shift. Spectrophotometers can compensate for this shift, making spectrophotometers a superior choice for accurate, repeatable color measurement.

Densitometers

In the printing and packaging industries, measuring ink density has historically been the preferred method of checking on-press quality (next to the "by-eye" method often preferred by long-time press operators). According to Brian Ashe, solutions architect for the Pantone Digital Business unit of X-Rite, "A densitometer is very good at reading process colors—cyan, magenta, yellow and black, the CMYK of the four-color process—because it basically is looking at the ink film that is being laid down on the substrate. But while densitometers are very good at checking density, they are not very good at looking at color. Actually, they don't see colors at all." It is also important to consider the fact that ink failures due to contamination can also cause issues. In these cases, density readings may appear fine, but these failures can only be detected by monitoring spectral values.

With today's spectrophotometers, not only can more accurate spectral values be measured, but companion software can inform the press operator exactly what needs to be done with ink key settings in order to ensure appropriate ink densities and/or to bring color back into tolerance, often before shifts are even visible to the human eye. A blended instrument such as the X-Rite eXact can offer both density and spectral measurements in a single instrument, sometimes called a spectrodensitometer.

KEY TAKEAWAY

Colorimeters and densitometers can play a useful role in the color measurement process, but they do not deliver the same color data as a spectrophotometer. Blended instruments (spectrocolorimeters or spectrodensitometers) can be a good answer for organizations seeking an affordable solution that incorporates some capabilities of each instrument type.

Applications

The uses for spectrophotometers are seemingly boundless. Color matching decisions are made every day by those comparing a reproduced object to a reference point. Spectrophotometry-assisted color measurement can be useful in areas such as:

- Establishing specifications and tolerances for acceptable color.
- Determining whether raw materials or other incoming components are acceptable and meet specifications.
- Verifying accurate formulation of inks and other colorants.
- Ensuring accurate colorant recipes in a test environment in the lab before going into production.
- Testing product during the manufacturing process to avoid expensive color shifts.
- Validating color performance to instill confidence in customers.
- Implementing good quality control processes for incoming finished goods or parts to be assembled.
- Establishing a common color language and communication process across the entire supply chain, whether local, regional or global.

KEY TAKEAWAY

Measuring, managing and communicating color by the numbers, using color measurement instruments and other color measurement and management techniques, is making a real difference to businesses around the globe and across all industries.

Find more information about how businesses are employing color measurement, management and communication techniques for less waste, faster time to market, improved product quality, higher customer satisfaction and increased profitability by visiting www.xrite.com/resources.aspx

Zero Moment of Truth

Google refers to the instant a purchase decision is made as the Zero Moment of Truth (ZMOT). It is made up of a series of micro-moments: Want-to-know moments, Want-to-go moments, Want-to-do moments, Want-to-buy moments.

Google says, “They’re all micro-moments, and they’re the new battleground for brands.” And color is an important part of making that happen -- at least 70% of the time, according to research.

Glossary

absolute white – In theory, a material that perfectly reflects all light energy at every visible wavelength. In practice, a solid white with known spectral reflectance data that is used as the "reference white" for all measurements of absolute reflectance. When calibrating a spectrophotometer, often a white ceramic plaque is measured and used as the absolute white reference.

absorb/absorption – Dissipation of the energy of electromagnetic waves into other forms (e.g., heat) as a result of its interaction with matter; a decrease in directional transmittance of incident radiation, resulting in a modification or conversion of the absorbed energy.

achromatic color – A neutral color that has no hue (white, gray or black).

additive primaries – Red, green and blue light. When all three additive primaries are combined at 100% intensity, white light is produced. When these three are combined at varying intensities, a gamut of different colors is produced. Combining two primaries at 100% produces a subtractive primary, either cyan, magenta or yellow:
100% red + 100% green = yellow
100% red + 100% blue = magenta
100% green + 100% blue = cyan
See subtractive primaries

appearance – An object's or material's manifestation through visual attributes such as size, shape, color, texture, glossiness, transparency, opacity, etc.

artificial daylight – Term loosely applied to light sources, frequently equipped with filters, that try to reproduce the color and spectral distribution of daylight. A more specific definition of the light source is preferred.

attribute – Distinguishing characteristic of a sensation, perception or mode of appearance. Colors are often described by their attributes of hue, chroma (or saturation) and lightness.

black – In theory, the complete absorption of incident light; the absence of any reflection. In practice, any color that is close to this ideal in a relative viewing situation — i.e., a color of very low saturationand very low luminance.

brightness – The dimension of color that refers to an achromatic scale, ranging from black to white. Also called lightness, luminous reflectance or transmittance (q.v.). Because of confusion with saturation, the use of this term should be discouraged.

c* – Abbreviation for chromaticity.

chroma/chromaticity – The intensity or saturation level of a particular hue, defined as the distance of departure of a chromatic color from the neutral (gray) color with the same value. In an additive color- mixing environment, imagine mixing a neutral gray and a vivid red with the same value. Starting with the neutral gray, add small amounts of red until the vivid red color is achieved. The resulting scale obtained would represent increasing chroma. The scale begins at zero for neutral

Glossary – continued next page

colors, but has no arbitrary end. Munsell originally established 10 as the highest chroma for a vermilion pigment and related other pigments to it. Other pigments with higher chroma were noted, but the original scale remained. The chroma scale for normal reflecting materials may extend as high as 20, and for fluorescent materials it may be as high as 30.

chromatic – Perceived as having a hue — not white, gray or black.

chromaticity coordinates (CIE) – The ratios of each of the three tris- timulus values X, Y and Z in relation to the sum of the three — designated as x, y and z respectively. They are sometimes referred to as the trichromatic coefficients. When written without subscripts, they are assumed to have been calculated for illuminant C and the 2° (1931) standard observer unless specified otherwise. If they have been obtained for other illuminants or observers, a subscript describing the observer or illuminant should be used. For example, x10 and y10 are chromaticity coordinates for the 10° observer and illuminant C.

chromaticity diagram (CIE) – A two-dimensional graph of the chromaticity coordinates (x as the abscissa and y as the ordinate), which shows the spectrum locus (chromaticity coordinates of monochromatic light, 380-770nm). It has many useful properties for comparing colors of both luminous and non-luminous materials.

CIE (Commission Internationale de l'Eclairage) – The International Commission on Illumination, the primary international organization concerned with color and color measurement.

CIE 1976 L*a*b* color space – A uniform color space utilizing an Adams-Nickerson cube root formula, adopted by the CIE in 1976 for use in the measurement of small color differences.

CIE 1976 L*u*v* color space – A uniform color space adopted in 1976. Appropriate for use in additive mixing of light (e.g., color TV).

CIE chromaticity coordinates – See chromaticity coordinates (CIE).

CIE chromaticity diagram – See chromaticity diagram (CIE).

CIE daylight illuminants – See daylight illuminants (CIE).

CIE luminosity function (y) – See luminosity function (CIE).

CIE standard illuminants – See standard illuminants (CIE).

CIE standard observer – See stan- dard observer (CIE).

CIE tristimulus values – See tris- timulus values (CIE).

CIELAB – A uniform (Opponent color scale) color space in which colors are located within a three-dimensional rectangular coordinate system; the three dimensions are lightness (L*), redness/greenness (a*) and yellowness/blueness (b*). CIELab is part of the current CIE recommendations. Also known as L*a*b*.

CIELAB (or CIE L*a*b*, CIE Lab) – Color space in which values L*, a* and b* are plotted using Cartesian coordinate system. Equal distances in the space approximately represent equal color differences. Value L* represents lightness; value a* represents the red/green axis; and value b* represents the yellow/blue axis. CIELAB is a popular color space for use in measuring reflective and transmissive objects.

CMC (Colour Measurement Committee of the Society of Dyes and Colourists of Great Britain) – Organization that developed and published in 1988 a more logical, ellipse-based equation based on L*C*h° color space for computing DE (see delta E*) values as an alternative to the rectangular coordinates of the CIELAB color space.

color – One aspect of appearance; a stimulus based on visual response to light, consisting of the three dimensions of hue, saturation and lightness.

color attribute – A three-dimensional characteristic of the appearance of an object. One dimension usually defines the lightness, the other two together define the chromaticity.

color difference – The magnitude and character of the difference between two colors under specified conditions.

color-matching functions – Relative amounts of three additive primaries required to match each wavelength of light. The term is generally used to refer to the CIE standard observer color-matching functions.

color measurement – Physical measurement of light radiated, transmitted or reflected by a specimen under specified condition and mathematically transformed into standardized colorimetric terms. These terms can be correlated with visual evaluations of colors relative to one another.

color model – A color-measurement scale or system that numerically specifies the perceived attributes of color. Used in computer graphics applications and by color measurement instruments.

color order systems – Systems used to describe an orderly three-dimensional arrangement of colors. Three bases can be used for ordering colors: 1) an appearance basis (i.e., a psychological basis) in terms of hue, saturation and lightness; an example is the Munsell System; 2) an orderly additive color mixture basis (i.e., a psychophysical basis); examples are the CIE System and the Ostwald System; and 3) an orderly subtractive color mixture basis; an example is the Plochere Color System based on an orderly mixture of inks.

color space – Three-dimensional solid enclosing all possible colors. The dimensions may be described in various geometries, giving rise to various spacings within the solid.

color specification – Tristimulus values, chromaticity coordinates and luminance value, or other color-scale values, used to designate a color numerically in a specified color system.

color temperature – A measurement of the color of light radiated by a black body while it is being heated. This measurement is expressed in terms of absolute scale, or degrees Kelvin. Lower Kelvin temperatures such as 2400K are red; higher temperatures such as 9300K are blue. Neutral temperature is white, at 6504K.

Glossary – continued next page

color wheel – The visible spectrum's continuum of colors arranged in a circle, where complementary colors such as red and green are located directly across from each other.

colorants – Materials used to create colors — dyes, pigments, toners, waxes, phosphors.
colorimeter – An optical measurement instrument that responds to color in a manner similar to the human eye — by filtering reflected light into its dominant regions of red, green and blue.

colorimetric – Of, or relating to, values giving the amounts of three colored lights or receptors — red, green and blue.

colorist – A person skilled in the art of color matching (colorant formulation) and knowledgeable concerning the behavior of colorants in a particular material; a tinter (q.v.) (in the American usage) or a shader. The word "colorist" is of European origin.

complements – Two colors that create neutral gray when combined. On a color wheel, complements are directly opposite from each other: blue/yellow, red/green and so on.

contrast – The level of variation between light and dark areas in an image.

CxF – Color eXchange Format, originally developed by X-Rite, has now been adopted as part of ISO 17972 as the new standard for seamless digital color communication. A CxF fie contains spectral data, L*a*b values, observer angle, illuminance, physical filters and can also contain color formulation information.

D65 – The CIE standard illuminant that represents a color temperature of 6504K. This is the color temperature most widely used in graphic arts industry viewing booths. See Kelvin (K).

daylight illuminants (CIE) – Series of illuminant spectral power distribution curves based on measurements of natural daylight and recommended by the CIE in 1965. Values are defined for the wavelength region 300 to 830nm. They are described in terms of the correlated color temperature. The most important is D65 because of the closeness of its correlated color temperature to that of illuminant C, 6774K. D75 bluer than D65 and D55 yellower than D65 are also used.

delta (D or Δ) – A symbol used to indicate deviation or difference.

delta E*, delta e* – The total color difference computed with a color difference equation (ΔEab or ΔEcmc). In color tolerancing, the symbol DE is often used to express Delta Error.

Delta E 2000 – Delta-E 2000 is the first major revision of the dE94 equation. Unlike dE94, which assumes that L* correctly reflects the perceived differences in lightness, dE2000 varies the weighting of L* depending on where in the lightness range the color falls

dye – A soluble colorant — as opposed to pigment, which is insoluble.

dynamic range – An instrument's range of measurable values, from the lowest amount it can detect to the highest amount it can handle.

electromagnetic spectrum – The massive band of electromagnetic waves that pass through the air in different sizes, as measured by wavelength. Different wavelengths have different properties, but most are invisible — and some completely undetectable — to human beings. Only wavelengths that are between 380 and 720 nanometers are visible, producing light. Waves outside the visible spectrum include gamma rays, x-rays, microwaves and radio waves.

emissive object – An object that emits light. Emission is usually caused by a chemical reaction, such as the burning gasses of the sun or the heated filament of a light bulb.

fluorescent lamp – A glass tube filled with mercury gas and coated on its inner surface with phosphors. When the gas is charged with an electrical current, radiation is produced. This, in turn, energizes the phosphors, causing them to glow.

gloss – An additional parameter to consider when determining a color standard, along with hue, value, chroma, the texture of a material and whether the material has metallic or pearlescent qualities. Gloss is an additional tolerance that may be specified in the Munsell Color Tolerance Set. The general rule for evaluating the gloss of a color sample is the higher the gloss unit, the darker the color sample will appear. Conversely, the lower the gloss unit, the lighter a sample will appear. Gloss is measured in gloss units, which use the angle of measurement and the gloss value (e.g. 60˚ gloss = 29.8). A 60˚ geometry is recommended by the American Society for Testing and Materials (ASTM) D523 standard for the general evaluation of gloss.

grayscale – An achromatic scale ranging from black through a series of successively lighter grays to white. Such a series may be made up of steps that appear to be equally distant from one another (such as the Munsell Value Scale), or it may be arranged according to some other criteria such as a geometric progres- sion based on lightness. Such scales may be used to describe the relative amount of difference between two similar colors.

hue – 1) The first element in the color-order system, defined as the attribute by which we distinguish red from green, blue from yellow, etc. Munsell defined five principal hues (red, yellow, green, blue and purple) and five intermediate hues (yellow- red, green-yellow, blue-green, purple-blue and red-purple. These 10 hues (represented by their corre- sponding initials R, YR, Y, GY, G,BG, B, PB, P and RP) are equally spaced around a circle divided into 100 equal visual steps, with the zero point located at the beginning of the red sector. Adjacent colors in this circle may be mixed to obtain continuous variation from one hue to another. Colors defined around the hue circle are known as chromatic colors. 2) The attribute of color by means of which a color is perceived to be red, yellow, green, blue, purple, etc. White, black and gray possess no hue.

illuminant – Mathematical description of the relative spectral power distribution of a real or imaginary light source — i.e., the relative energy emitted by a source at each wavelength in its emission spectrum. Often used synonymously with “light source” or “lamp,” though such usage is not recommended.

illuminant A (CIE) – Incandescent illumination, yellow-orange in color, with a correlated color temperature of 2856K. It is defined in the wave- length range of 380 to 770nm.

illuminant C (CIE) – Tungsten illumination that simulates average daylight, bluish in color, with a correlated color temperature of 6774K.

Glossary – continued next page

illuminants D (CIE) – Daylight illuminants, defined from 300 to 830nm (the UV portion 300 to 380nm being necessary to correctly describe colors that contain fluorescent dyes or pigments). They are designated as D, with a subscript to describe the correlated color temperature; D65 is the most commonly used, having a correlated color temperature of 6504K, close to that of illuminant C. They are based on actual measurements of the spectral distribution of daylight.

integrating sphere – A sphere manufactured or coated with a highly reflective material that diffuses light within it.

Kelvin (K) – Unit of measurement for color temperature. The Kelvin scale starts from absolute zero, which is -273° Celsius.

L*a*b* – A uniform (Opponent color scale) color space in which colors are located within a three-dimensional rectangular coordinate system; the three dimensions are lightness (L*), redness/greenness (a*) and yellowness/blueness (b*). Also known as CIELAB.

light – 1) Electromagnetic radiation of which a human observer is aware through the visual sensations that arise from the stimulation of the retina of the eye. This portion of the spectrum includes wavelengths from about 380 to 770nm. Thus, to speak of ultraviolet light is incorrect because the human observer cannot see radiant energy in the ultraviolet region. 2) Adjective meaning high reflectance, transmittance or level of illumination as contrasted to dark, or low level of intensity.
light source – An object that emits light or radiant energy to which the human eye is sensitive.
The emission of a light source can be described by the relative amount of energy emitted at each wavelength in the visible spectrum, thus defining the source as an illuminant. The emission also may be described in terms of its correlated color temperature.

lightness – Perception by which white objects are distinguished from gray, and light-colored objects from dark-colored.

luminosity function (y) (CIE) – A plot of the relative magnitude of the visual response as a function of wavelength from about 380 to 780nm, adopted by CIE in 1924.

metamerism – A phenomenon exhibited by a pair of colors that match under one or more sets of illuminants (be they real or calculated), but not under all illuminants.

Munsell Color System – The color identification of a specimen by its Munsell hue, value and chroma as visually estimated by comparison with the Munsell Book of Color.

Munsell Scale – is a color space that specifies colors based on three color dimensions: hue, value (lightness), and chroma (color purity). It was created by professor Albert H. Munsell in the first decade of the 20th century and adopted by the USDA as the official color system for soil research in the 1930's.

nanometer (nm) – Unit of length equal to 10-9 meter (a.k.a. one billionth of a meter, or a millimicron).

observer – The human viewer who receives a stimulus and experiences a sensation from it. In vision, the stimulus is a visual one and the sensation is an appearance.

observer, standard – See standard observer.

radiant energy – A form of energy consisting of the electromagnetic spectrum, which travels at 299,792 kilometers/second (186,206 miles/second) through a vacuum, and more slowly in denser media (air, water, glass, etc.). The nature of radiant energy is described by its wavelength or frequency, although it also behaves as distinct quanta ("corpuscular theory"). The various types of energy may be transformed into other forms of energy (electrical, chemical, mechanical, atomic, thermal, radiant), but the energy itself cannot be destroyed.

reflectance – The ratio of the intensity of reflected radiant flux to that of incident flux. In popular usage, it is considered the ratio of the intensity of reflected radiant energy to that reflected from a defined reference standard.

reflectance, specular – See specular reflectance.

reflectance, total – See total reflectance.

saturation – The attribute of color perception that expresses the amount of departure from a gray of the same lightness. All grays have zero saturation (ASTM). See chroma/chromaticity.

scattering – Diffusion or redirection of radiant energy encountering particles of different refractive index. Scattering occurs at any such interface, at the surface, or inside a medium containing particles.

Spectral data – The most precise description of the color of an object. An object¹s color appearance results from light being changed by an object and reflected to a viewer. Spectral data is a description of how the reflected light was changed. The percentage of reflected light is measured at several intervals across its spectrum of wavelengths. This information can be visually represented as a spectral curve.

spectral power distribution curve – Intensity of radiant energy as a function of wavelength, generally given in relative power terms.

Spectral reflectance – The reflectance spectrum or spectral reflectance curve is the plot of the reflectance as a function of wavelength.

spectrophotometer – Photometric device that measures spectral transmittance, spectral reflectance or relative spectral emittance.

spectrophotometric curve – A curve measured on a spectrophotometer; a graph with relative reflectance or transmittance (or absorption) as the ordinate, plotted with wavelength or frequency as the abscissa.

spectrum – Spatial arrangement of components of radiant energy in order of their wavelengths, wave number or frequency.

specular gloss – Relative luminous fractional reflectance from a surface in the mirror or specular direction. It is sometimes measured at 60˚ relative to a perfect mirror.

Glossary – continued next page

specular reflectance – Reflectance of a beam of radiant energy at an angle equal but opposite to the incident angle; the mirror-like reflectance. The magnitude of the specular reflectance on glossy materials depends on the angle and the difference in refractive indices between two media at a surface. The magnitude may be calculated from Fresnel's Law.

specular reflectance excluded (SCE) – Measurement of reflectance made in such a way that the specular reflectance is excluded from the measurement; diffuse reflectance. The exclusion may be accomplished by using 0° (perpendicular) incidence on the samples. This then reflects the specular component of the reflectance back into the instrument by use of black absorbers or light traps at the specular angle when the incident angle is not perpendicular, or in directional measurements by measuring at an angle different from the specular angle.

specular reflectance included (SCI) – Measurement of the total reflectance from a surface, including the diffuse and specular reflectances.

standard – A reference against which instrumental measurements are made.

standard illuminants (CIE) – Known spectral data established by the CIE for four different types of light sources. When using tristimulus data to describe a color, the illuminant must also be defined. These standard illuminants are used in place of actual measurements of the light source.

standard observer (CIE) – 1) A hypothetical observer having the tristimulus color-mixture data recommended in 1931 by the CIE for a 2° viewing angle. A supplementary observer for a larger angle of 10° was adopted in 1964. 2) The spectral response characteristics of the average observer defined by the CIE. Two such sets of data are defined, the 1931 data for the 2° visual field (distance viewing) and the 1964 data for the annular 10° visual field (approximately arm's length viewing). By custom, the assumption is made that if the observer is not specified, the tristimulus data has been calculated for the 1931, or 2° field observer. The use of the 1964 data should be specified.

subtractive primaries – Cyan, magenta and yellow. Theoretically, when all three subtractive primaries are combined at 100% on white paper, black is produced. When these are combined at varying intensities, a gamut of different colors is produced. Combining two primaries at 100% produces an additive primary, either red, green or blue:
100% cyan + 100% magenta = blue
100% cyan + 100% yellow = green
100% magenta + 100% yellow = red

tint – 1) verb: To mix white pigment with absorbing (generally chromatic) colorants. 2) noun: The color produced by mixing white pigment with absorbing (generally chromatic) colorants. The resulting mixture is lighter and less saturated than the color without the white added.

total reflectance – Reflectance of radiant flux reflected at all angles from the surface, thus including both diffuse and specular reflectances.

transparent – Describes a material that transmits light without diffusion or scattering.

tristimulus – Of, or consisting of, three stimuli; generally used to describe components of additive mixture required to evoke a particular color sensation.

tristimulus colorimeter – An instrument that measures tristimulus values and converts them to chromaticity components of color.

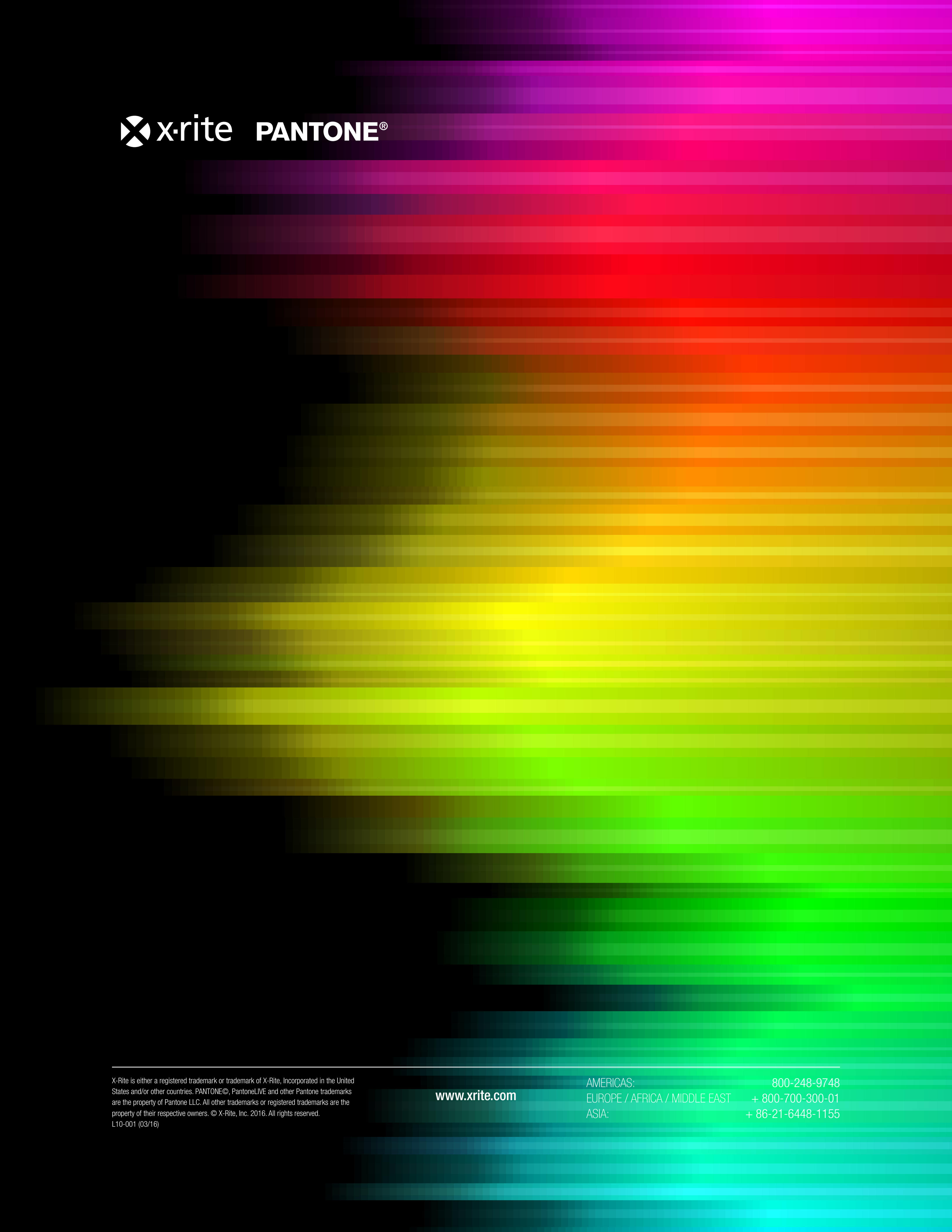
tristimulus values (CIE) – Percentages of the components in a three-color additive mixture necessary to match a color; in the CIE system, they are designated as X, Y and Z. The illuminant and standard observer color-matching functions used must be designated; if they are not, the assumption is made that the values are for the 1931 observer (2° field) and illuminant C. The values obtained depend on the method of integration used, the relationship of the nature of the sample and the instrument design used to measure the reflectance or transmittance. Tristimulus values are not, therefore, absolute values characteristic of a sample, but relative values dependent on the method used to obtain them. Approximations of CIE tristimulus values may be obtained from measurements made on a tristimulus colorimeter that gives measurements generally normalized to 100. These must then be normalized to equivalent CIE values. The filter measurements should be properly designated as R, G and B instead of X, Y and Z.

value – Indicates the degree of lightness or darkness of a color in relation to a neutral gray scale. The scale of value (or V, in the Munsell system of color notation) ranges from 0 for pure black to 10 for pure white. The value scale is neutral or without hue.

X – 1) One of the three CIE tristimulus values; the red primary. 2) Spectral color-matching functions of the CIE standard observer used for calculating the X tristimulus value. 3) One of the CIE chromaticity coordinates calculated as the fraction of the sum of the three tristimulus values attributable to the X value.

Y – 1) One of the three CIE tristimulus values, equal to the luminous reflectance or transmittance; the green primary. 2) Spectral color-matching function of the CIE standard observer used for calculating Y tristimulus value. 3) One of the CIE chromaticity coordinates calculated as the fraction of the sum of the three tristimulus values, attributable to the Y value.

Z – 1) One of the three CIE tristimulus values; the blue primary. 2) Spectral color-matching function of the CIE standard observer used for calculating the Z tristimulus value. 3) One of the CIE chromaticity coordinates calculated as the fraction of the sum of the three tristimulus values attributable to the Z primary.



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