

Optical metrology for LEDs and solid state lighting

Yoshi Ohno

National Institute of Standards and Technology
100 Bureau Drive, Gaithersburg, MD 20899 USA.

ABSTRACT

The performance of Light Emitting Diodes (LEDs), including efficiency, flux level, lifetime, and the variation of color, is advancing at a remarkable pace. LEDs are increasingly used for many applications including automotive, aviation, display, transportation and special lighting applications. White LEDs are expected for general lighting applications (solid state lighting) in the near future. Thus, accurate measurements of LEDs and appropriate standards are increasingly important. This paper reviews photometric, radiometric, and colorimetric quantities used for LEDs, and discusses the current state of optical measurements of LEDs and standardization efforts in International Commission on Illumination (CIE). The paper also touches on the issue of color quality (e.g., Color Rendering Index) of light expected from solid state lighting, and the need for a new metric. The calibration facilities and services for LEDs established at NIST are also discussed.

Keywords: Color rendering, Colorimetry, Luminous efficacy, Measurement, Photometry, Solid state lighting, LED, White LED

1. INTRODUCTION

There have been significant advancements in light-emitting diodes (LEDs) in recent years. High brightness LEDs are now available in many colors and their efficiency has recently been greatly improved. LEDs are being utilized in many single-color applications at a great pace, such as traffic lights, emergency lights, automotive lights, aviation lights, outdoor color displays, and niche lighting applications. White LEDs are also now available, and their performance is improving year by year. White LEDs are produced by mixture of multi-color LEDs (e.g., RGB combination), by use of a phosphor excited by blue LED emission, or by multiple phosphors excited by UV LED emission. White LEDs are already being introduced into niche lighting applications, and as their performance improves, they are highly expected for use in general lighting due to their potential high efficiency. Solid state lighting is promising because it has theoretically a very high luminous efficacy (theoretical limit of white LED light ≈ 400 lm/W). Many of white LEDs currently commercially available have a luminous efficacy of ≈ 30 lm/W, already higher than incandescent lamps. Nearly 100 lm/W has been achieved on laboratory prototypes, which is the level of the current high-efficiency fluorescent lamps. Solid state lighting (SSL) will have great impact for the potential of huge energy savings. In the United States, lighting consumes 22% of electricity and 8% of total energy. The U.S. Department of Energy expects that solid state lighting will reduce the energy consumption by lighting to a half of the current level by 2025¹. This will also lead to 10% reduction in greenhouse gas emissions. The goal of SSL industry in a shorter term is to achieve 150 lm/W white LED lamps by 2012.

Such a goal for SSL, however, is a great challenge. There are many technical hurdles to overcome for SSL to be able to substantially penetrate into general lighting market. For example, much improvement is needed for the internal quantum efficiency (Q.E.) of LEDs. The yellow-green region (≈ 540 to ≈ 570 nm, called the “green hole”) suffers from very low efficiency (less than 10% Q.E.) while red LEDs already achieve more than 80% Q.E and blue LEDs have Q.E. of $\approx 50\%^2$. The green region is important for multi-chip white LEDs to produce good color rendering. Light extraction efficiency is also a difficulty. About 50% of the light from the chip is trapped inside the encapsulation and lost. Phosphor type white LEDs suffer from the loss of quantum efficiency of phosphors (currently about 70%). Flux per chip is very important for real application of LEDs for lighting, as lighting requires a large amount of luminous flux. Finally, cost is probably the largest hurdle for penetration into lighting market. The price per kilo lumen of white LEDs is currently two orders of magnitude higher than traditional lamps.

In addition to lumens per watt, color rendering (how natural the colors of objects look under a given illumination) is an important characteristic for light sources for general lighting. White LEDs have great freedom in their spectral design and are expected to produce color rendering much better than the traditional light sources. However, color rendering performance is generally in trade-off relationship with luminous efficacy. Inadequate optimization for color rendering would lead to loss of energy, thus the metric for color rendering is extremely important to the energy aspect. For example, there are some views that good color rendering requires continuous broadband spectra throughout the visible spectral region. Such spectra would have very low luminous efficacy and lead to a waste of energy. The Color Rendering Index (CRI)³ defined by the Commission Internationale de l'Éclairage (CIE) is currently the only internationally agreed-upon metric and is widely used, but it is known to have several deficiencies⁴, especially when used for LED sources. Research work is in progress to investigate the problems and develop an improved metric for color rendering that works well for all type of light sources⁵⁻⁷.

As the applications of LEDs expand, measurements of LEDs are becoming increasingly important in commerce and trade. However, there are large variations in measurements reported (40 % to 50 % discrepancies in luminous intensity and total flux measurement in the industry⁸), in contrast to typical traditional lamp measurements, which agree typically within a few percent between different companies. This is due to the large differences in spectral and spatial characteristics of LEDs compared with traditional light sources. CIE published a recommendation on the measurements of LEDs in 1997 (CIE Publication 127⁹), but it is not sufficient, and a revision of this publication is in progress¹⁰. An overview of photometric and colorimetric quantities measured for LEDs are provided below and some critical issues on LED measurements including new recommendations from the CIE are discussed.

2. PHOTOMETRIC AND RADIOMETRIC QUANTITIES FOR LEDs

Table 1 shows photometric and radiometric quantities typically used for LEDs. The table shows the photometric quantities and their corresponding radiometric quantities side by side. These quantities and units are officially defined in international standards¹¹⁻¹³. Refer to these standards for the detailed official definitions of the quantities and units. Photometric quantities are used for LEDs for illumination and signaling purposes (visual applications). Luminous intensity (candela) and total luminous flux (lumen) are the most important photometric quantities for visual applications. Radiometric quantities are used for all LEDs, particularly for ultraviolet and infrared LEDs.

Table 1. Photometric and Radiometric Quantities typically measured for LEDs.

Photometric quantity (unit)	Symbol	Radiometric quantity (unit)	Symbol
Luminous intensity (cd)	I_v, I_v	Radiant intensity (W/sr)	I_e, I_e
Averaged LED Luminous Intensity (cd)	$I_{LED A}$ $I_{LED B}$	Averaged LED Radiant Intensity (W/sr)	$I_{e,LED A}$ $I_{e,LED B}$
Total luminous flux (lm)	Φ_v, Φ_v	Total radiant flux, optical power (W)	Φ_e, Φ_e
Luminous efficacy (lm/W)	η_v	Radiant efficiency (external Q.E.)	η_c
Luminance (cd/m ²)	L, L_v	Radiance (W/sr/m ²)	L, L_e
Spatial intensity distribution		Spatial intensity distribution	
		Spectral power distribution	

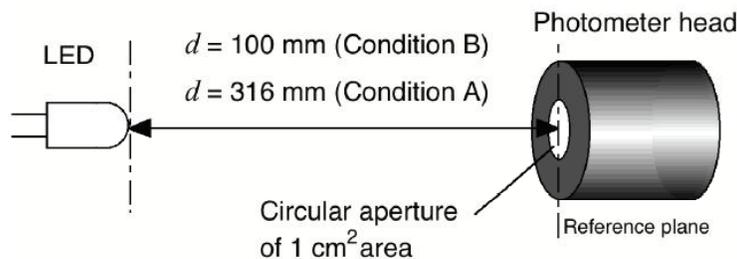


Fig. 1. Geometry for CIE Averaged LED Intensity.

The *Averaged LED (Luminous/Radiant) Intensity* is defined by CIE¹³ with the geometry shown in Fig. 1. This quantity is recommended for individual LEDs having a lens optic (such as a 5 mm epoxy type). Such LEDs do not behave as a point source, and measured luminous intensity values tend to vary significantly with the measurement distance and photometer aperture size. This standardized geometry will avoid such measurement variations and enable accurate comparison of measured values. The normal *luminous intensity* may be used for other LEDs measured as a point source (with a sufficiently large distance).

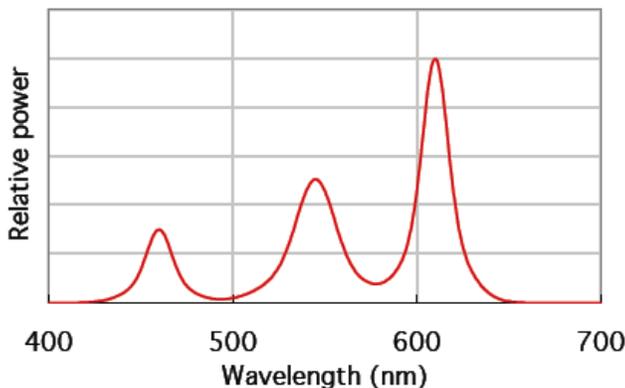


Fig. 2. An example of an RGB white LED model spectrum (peaks at 460 nm, 543 nm, and 610 nm) mixed for 3000 K. white).

The energy efficiency of a light source is evaluated by *luminous efficacy of a source* (often called simply “luminous efficacy”), which is the ratio of *luminous flux* (lumen) emitted by the source to the input electrical power (watt). “Wall plug efficiency” is often used, but it is not an official term. The luminous efficacy of a source, η_v [lm/W], is determined by two factors:

$$\eta_v = \eta_e \cdot K, \tag{1}$$

where η_e is the *radiant efficiency* of the source (ratio of output radiant flux to input electrical power; “external quantum efficiency” is often used with the same meaning). K is the *luminous efficacy of radiation* (ratio of luminous flux to radiant flux, denoted as LER in this paper), and is determined by the spectral distribution $S(\lambda)$ of the source as given by:

$$K = \frac{K_m \int_{\lambda} V(\lambda) S(\lambda) d\lambda}{\int_{\lambda} S(\lambda) d\lambda}, \text{ where } K_m = 683 \text{ [lm/W]}. \tag{2}$$

The $K_m=683$ lm/W comes from the definition of the candela, since monochromatic radiation at 555 nm (at the peak of the $V(\lambda)$ curve) is defined to have 683 lumens per watt. The LER is the theoretical maximum luminous efficacy of a light source of a given spectral distribution $S(\lambda)$. For example, a white LED spectrum as shown in Fig. 2 (an RGB white LED model described in Reference [7]) has a LER of 403 lm/W with decent color rendering ($R_a=85$). With a 50% external quantum efficiency for each R, G, and B LED, 200 lm/W luminous efficacy (of a source) would be achieved.

3. COLORIMETRIC QUANTITIES FOR LEDS

Table 2. Colorimetric Quantities for LEDs.

Color Quantity	Usage
Chromaticity coordinates $(x, y), (u', v')$	For all LEDs
Correlated Color Temperature [K]	For white LEDs
Color Rendering Index	For white LEDs
Dominant wavelength [nm]	For single-color LEDs
Peak wavelength [nm]	For single-color LEDs

Table 2 shows typical colorimetric quantities used for LEDs. These quantities are officially defined in CIE publications^{12,13}. Chromaticity coordinates (x, y) and (u', v') are both current CIE recommendations and are widely used. The (x, y) diagram, however, is very non-uniform in terms of color differences. Fig. 3 shows the minimum perceivable color differences (magnified 10 times), known as *Macadam Ellipses*, plotted on both diagrams. For example, the color differences of green LEDs would be much exaggerated on the (x, y) diagram. The (x, y) diagram has a long history and widely used. The nonuniformity is less problematic for white light sources, but it should be noted when the (x, y) diagram is used for single-color LEDs. The (u', v') diagram is generally recommended for all colored light sources.

The correlated color temperature (CCT) is defined as the temperature [K] of the Planckian radiator whose chromaticity is closest to that of a given stimulus on the $(u', \frac{2}{3}v')$ chromaticity diagram (now obsolete 1960 (u, v) diagram)¹³. CCT is valid only within the chromaticity range of 0.05 from Planckian locus on the $(u', \frac{2}{3}v')$ diagram.

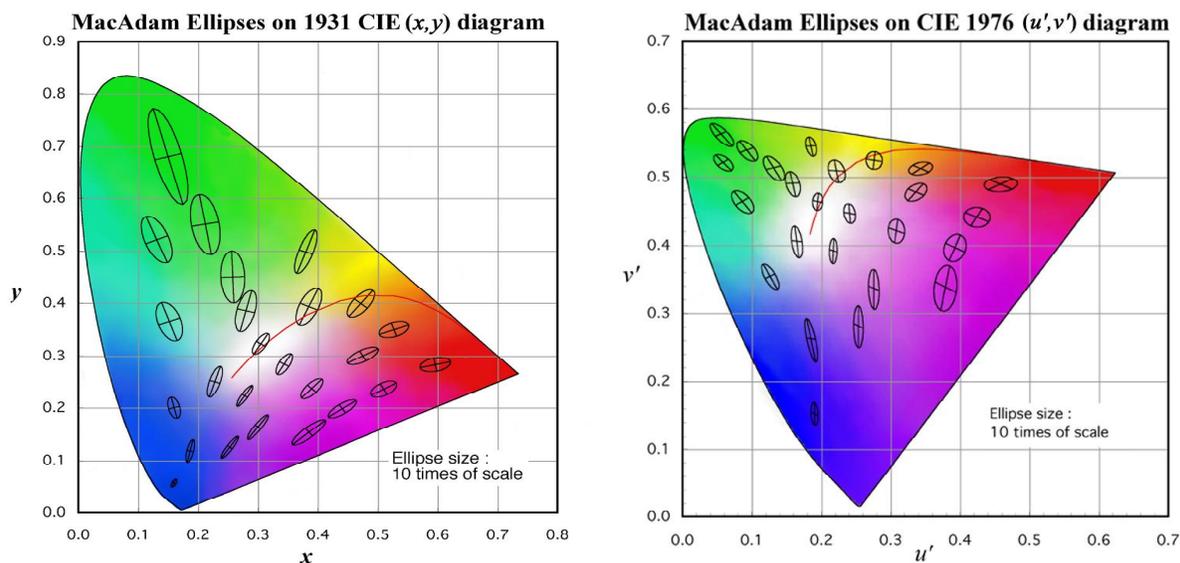


Fig. 3. MacAdam Ellipses on CIE (x, y) and (u', v') diagrams.

The CRI is currently the only internationally agreed-upon metric for color rendering evaluation. The procedure for the calculation is, first, to calculate the color differences ΔE_i (in the 1964 $W^*U^*V^*$ uniform color space – now obsolete) of 14 selected Munsell samples when illuminated by a reference illuminant and when illuminated by a given illumination. The first eight samples are of medium chromatic saturation, and the last six are highly saturated colors (red, yellow, green, and blue), the typical color of a Caucasian complexion, and the typical color of a green leaf. The reference illuminant is matched to the CCT of the test source and is the Planckian radiation for test sources having a correlated color temperature (CCT) $< 5\,000$ K, or a phase of daylight for test sources having $\text{CCT} \geq 5\,000$ K. The process incorporates the von Kries chromatic adaptation transformation. The *Special Color Rendering Indices* R_i for each color sample is obtained by:

$$R_i = 100 - 4.6 \Delta E_i \quad ; (i=1, \dots, 14). \quad (3)$$

This gives the evaluation of color rendering for each particular sample. The *General Color Rendering Index* R_a is given as the average of the first eight color samples:

$$R_a = \sum_{i=1}^8 R_i / 8 \quad . \quad (4)$$

The score for perfect color rendering (zero color differences) is 100. For near monochromatic sources, the score can become negative.

The CRI, however, is known to have deficiencies, and fails to work properly for many white LED light sources. The $W^*U^*V^*$ object color space is obsolete and very nonuniform. The standard eight samples used for the calculation of the General Color Rendering Index are all medium saturated colors, and even if R_a is high, saturated colors can appear very poorly. This problem is prominent for sources having narrow band peaks such as RGB white LEDs. Also, the CRI does not take into account the direction of color shifts. Decreases of chroma produce negative effects while increases of chroma often have positive effects. To give solutions to these problems, based on the detailed computational analysis of these problems^{6,7}, a new metric for color rendering, the “Color Quality Scale (CQS)” is proposed and being developed at NIST¹⁴.

4. MEASUREMENT OF LEDS

LEDs have very different spectral and spatial characteristics from traditional incandescent and discharge lamps for illumination. The photometry of traditional lamps has been well established, but measurements of LEDs are not as uniform as they should be, and large discrepancies (as much as 50%) of measurement results are often reported. The variations are primarily caused by differences in measurement methods and conditions, and errors in instruments. CIE 127⁹ prescribed the standard measurement geometry for luminous intensity measurements for LEDs –Averaged LED Intensity– as introduced in the earlier section. This has served well to improve luminous intensity measurements, but problems in other measurements have not been well addressed. To further improve the accuracy of LED measurements in the industry, CIE 127 is being revised in the CIE Technical Committee (TC) 2-45 to add further recommendations on total luminous flux measurements and spectral measurements.

One of the dominant causes of measurement discrepancy in total luminous flux measurement comes from ignoring the backward and sideway emissions of LEDs. Even though the LED chip is emitting light only in the forward direction, significant amounts of light are trapped in the LED encapsulation, and emitted backwards. Some types of LED have as much as 30% of flux emitted backward. Fig. 4 shows the old practice and the new recommendation for the integrating sphere geometry of total luminous flux measurement. In the old practice, the backward emission of the test LED is totally lost and the total luminous flux cannot be measured accurately. In the new recommendation (draft), the test LED is mounted in the center of the sphere so that the light emitted in the entire solid angle (4π) is measured accurately.

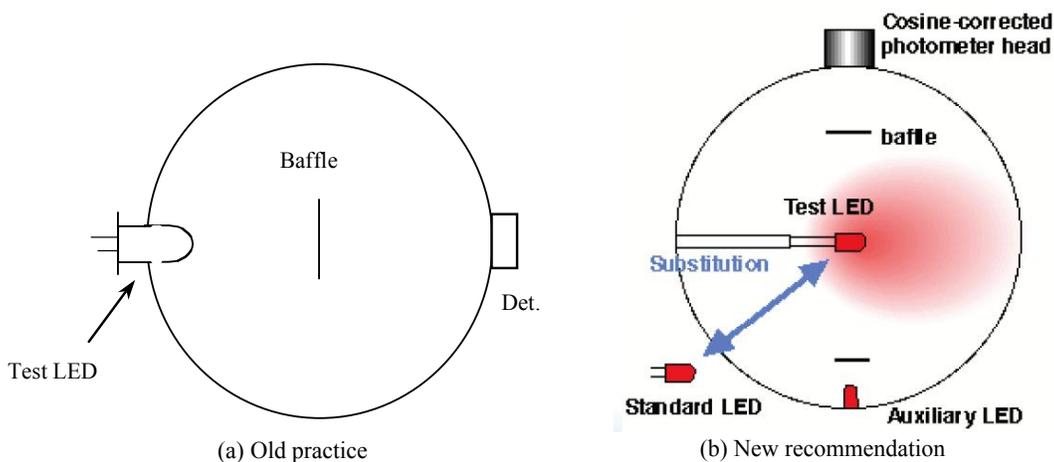


Fig. 4. Integrating sphere geometry for total luminous flux measurement of LEDs. (a) the old recommendation in the current version (b) the new recommendation in the revision of CIE 127 (draft).

In many applications, however, backward emissions, or even sideway emissions are not useful, and the flux emitted only in a limited solid angle may be meaningful. For such a purpose, a new quantity, *Partial LED Flux* is proposed, Fig. 5. It is defined as the flux leaving the LED and propagating within a given cone angle, centered from the LED’s mechanical axis. Any flux emitted in the directions other than in this cone angle is ignored.

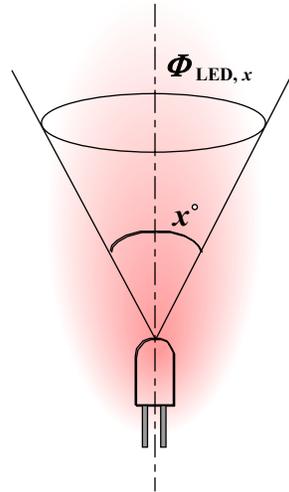


Fig. 5. Concept of Partial LED Flux.

Another major cause of error in LED total luminous flux measurements, as well as in luminous intensity measurements, is the spectral mismatch of photometers. Even if the photometer's spectral responsivity is well matched to $V(\lambda)$, the match near the wings of the $V(\lambda)$ curve are generally poor. Even high quality photometers can cause significant spectral mismatch errors (20% or 30%) for blue (≈ 460 nm) and red (≈ 650 nm) LEDs. The correction of spectral mismatch error is possible but not convenient to perform in the industry. As a solution to this problem, spectroradiometers are increasingly used for LED measurements. The revision of CIE 127 is to give recommendations on using spectroradiometers not only for measurement of color, but also for luminous intensity and luminous flux of LEDs; in other words, to use a spectroradiometer as a "perfect" $V(\lambda)$ -corrected photometer, which does not cause spectral mismatch errors (theoretically).

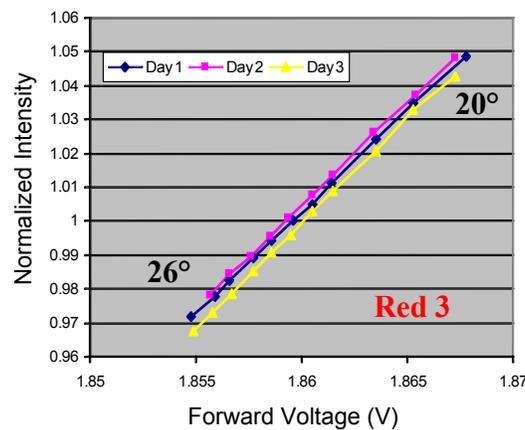


Fig. 6. Relationship between the relative luminous intensity and forward voltage of a red LED with change of ambient temperature.

Measurements of individual LEDs were discussed above. Many questions and concerns also exist in the measurement of LED clusters and arrays. CIE TC2-50 (Measurement of the optical properties of LED clusters and arrays) has recently started to prepare a technical report for the measurement of the optical properties of visible LED clusters and arrays and to give recommendations for definitions, measurement methods, and measurement conditions for various clusters and arrays of LEDs, including static displays and signs. Also the Illuminating Engineering Society of North America (IESNA), Testing Procedures Committee has Project 78 - Guide for Measurement of LEDs. The purpose of this project

is to develop a guide for appropriate methods and equipment to measure the output of LED fixtures for lighting and signaling purposes.

There are many considerations required for accurate measurements of LEDs. Another common cause of LED measurement variations is their temperature dependence. Fig. 6 shows the change of luminous intensity (and forward voltage) with the change of ambient temperature. This red LED example shows significant sensitivity to the temperature. With this LED example, however, the temperature and forward voltage have a linear relationship, thus, it is possible to make corrections for ambient temperature difference by monitoring forward voltage. For high accuracy applications, temperature controlled LEDs are commercially available. Such LEDs can be used as reference standard LEDs to calibrate or verify the accuracy of instruments.

5. CALIBRATION FACILITIES FOR LEDs AT NIST

To provide traceability of LED measurements, facilities and procedures for LED photometric and colorimetric calibrations have been established at NIST. Calibration services are provided for LED total luminous flux, Averaged LED Luminous Intensity (Geometry A and B), and color quantities such as chromaticity coordinates (x , y) and (u' , v'), dominant wavelength, correlated color temperature, and CRI (for white LEDs). The Averaged LED Intensity is measured on the NIST photometric bench using LED reference standard photometers designed for the CIE geometry. The total luminous flux of LEDs is measured using the NIST 2.5 m integrating sphere as shown in Fig. 7. Such a big sphere is not required for LED measurements, but this sphere is the one used for the NIST realization of the lumen, and it provides the lowest uncertainty calibration at NIST. For both luminous intensity and luminous flux, the calibration uncertainty is typically 3% (some single color LEDs) to 1% (white LED) depending on LED characteristics. The color quantities are measured with a reference double-grating spectroradiometer. CIE-B geometry is typically used for the spectroradiometric measurement of LEDs. The uncertainty of color calibration is typically less than 0.001 in (u' , v') for all LED colors. The details of these NIST calibration facilities for LEDs are available in Reference [15]. NIST also has established a capability to measure total radiant flux (watt) of UV and deep blue LEDs (360 nm to 450 nm) using a radiometric detector and spectroradiometer with the 2.5 m sphere¹⁶. A calibration service for total radiant flux of such LEDs is also available. New calibration services are being developed for total spectral radiant flux standards, which are required to calibrate integrating sphere systems with a spectroradiometer¹⁷.



Fig. 7. NIST 2.5 m integrating sphere and the LED mount.

6. CONCLUSIONS

Applications of LEDs are expanding at a rapid pace, and solid state lighting is promising for huge energy savings for general lighting. As the applications of LEDs grow, accurate measurements of LEDs are increasingly important. For more uniformity of LED measurements, CIE Publication 127 is being revised. New recommendations will be given for total luminous flux measurements and spectroradiometric measurements. Calibration facilities for LEDs have been

established at NIST, and various calibration services are available, including Averaged Intensity, total luminous flux, total radiant flux, chromaticity coordinates, dominant wavelength, correlated color temperature, etc.

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