Shedding Light on the Candela

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Though the candela is one of the seven SI base units, it receives little attention from physics teachers. This paper will discuss the history of the candela, its measurement techniques (photometry), and its relation to the lumen. The luminous properties of incandescent and fluorescent lamps are compared. Of the SI base units, only the candela is linked to the peculiarities of human perception.

A peek into our physical science prep room indicates that the semester is about to begin. Several carts are piled high with two-liter jugs, cubic-centimeter toys, meter sticks, and kilogram masses. These props are used to (re)acquaint our students with the SI system of measurement. A typical presentation might begin with a discussion of the seven base units: meter, kilogram, second, ampere, kelvin, mole, and — what's the last one? — oh yes, the candela. Few if any words are devoted to the candela. Textbook authors usually avoid the topic as well.[1] The purpose of this paper is to march the candela out into the open.

What Is the Candela?

Loosely speaking, the candela is used to describe the intensity *of the visible portion of the EM spectrum* given off by a light source, i.e., luminous intensity (I_V, with the V standing for visual). Luminous intensity is to be contrasted with radiant intensity, which covers emission over the entire EM spectrum. Intensity, in this context, refers to power projected per unit solid angle (see Fig. 1). It quantifies (in watts per steradian) how concentrated the radiated energy is in a particular direction.

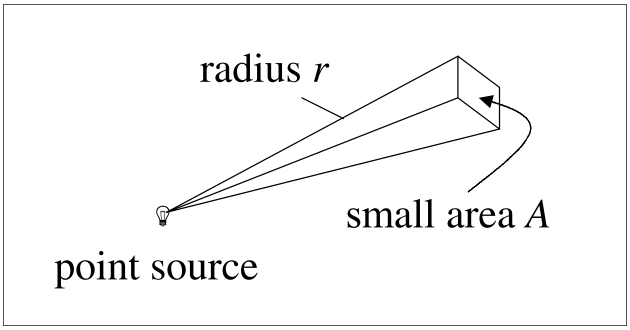

Fig. 1. The solid angle, in steradians, associated with area A is defined as A divided by r^2. Light projected in all directions covers 4π steradians. Hence, one steradian is about one-twelfth of full spherical projection.

Former Standards of Luminous Intensity

Starting in the mid- to late-1800s, luminous intensity (formerly called *candle power*) was quantified using actual flame candles. Different laboratories and governments maintained their own "standard" candles. By the turn of the 20th century, more than 10 such standards existed. For example, the Prussian Vereinskerze was defined as the luminous intensity of "a cylindrical candle made of paraffin, with a diameter of 20 millimeters and a length of 314 millimeters, burning with a flame height of 50 millimeters. The wick consisted of 25 strands of twisted cotton thread."[2] The French used an oil lamp with a mechanical draft, the British used a whale-oil candle, and so on. By present-day standards, most of these candles had luminous intensities (in the horizontal direction) of approximately one candela. The name can-

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dela (introduced in 1948) is apt, as the unit is roughly the light intensity of an ordinary table candle.

The brightness of a candle is not very reliable, however. In 1921, the Commission Internationale de l'Éclairage (CIE, or International Commission on Illumination) certified the international candle, which was realized by a carbon-filament incandescent lamp. While a great improvement over candles, the light output of a fixed-voltage incandescent lamp changes slightly as the filament ages. An even better standard was sought.

Blackbody radiation was the answer. For a perfect blackbody radiator, the shape of the emission spectrum and the total emitted power depend only upon the temperature of the radiator. The melting point of platinum at atmospheric pressure (1769°C) provided a reproducible temperature. After World War II, the candela was established as the luminous intensity, in the perpendicular direction, of 1/60 cm^2 of molten platinum at its melting point. This definition prevailed until 1979.

All of the above definitions are based on standard *sources* of light. If a lightbulb manufacturer wishes to quantify the brightness of a particular bulb, he/she must compare it against the standard. But specifically what aspect of the two sources is to be compared, and how is this comparison achieved?

Visual Photometry: Determining the Luminous Intensity of a Light Source Using a Human Observer

Photometry is the science of *visible* light measurement. (It is to be contrasted with radiometry, which studies emissions over all wavelengths.) Photometry seeks to quantify the brightness *perceived* by a human observer. Two sources of light are assigned equal luminous intensities if an "average" human judges their brightnesses to be equal. The Bunsen grease-spot photometer, invented in 1843, is a simple apparatus for performing such brightness comparisons (see Fig. 2).[3,4] An oily spot on a piece of white paper allows more light transmission than the surrounding paper. When the paper is illuminated from the front, the grease spot looks dark in comparison to the surrounding paper. When back lit, the spot instead looks brighter. Hence, when the paper receives equal illumination from front and back, the spot no longer stands out. The distance of the test source to the screen (d_2) is adjusted to provide such a matching condition. Since the solid angle subtended by the grease spot varies as the inverse square of the distance to the source, it follows that the luminous intensity of source 2 is related to that of source 1 by

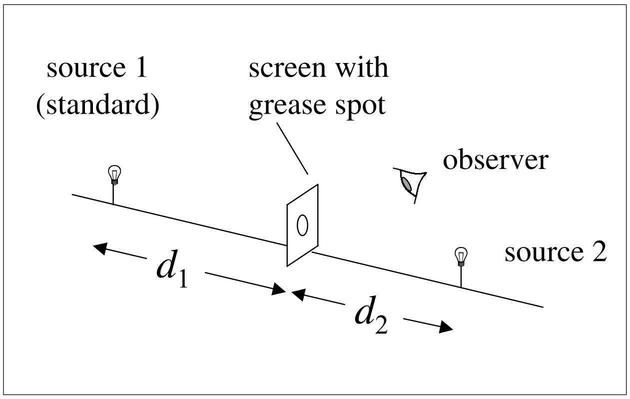

Fig. 2. Crude photometer using Bunsen grease spot. The luminous intensity at the screen varies as the inverse square of the source's distance to the screen. Distance d_2 is adjusted until the grease spot cannot be distinguished from the rest of the screen. At that point, the screen is equally illuminated from both sides.

$$I_{V_1} = \left(\frac{d_1}{d_2}\right)^2 I_{V_2}, \tag{1}$$

where I_{V_1} and I_{V_2} are the luminous intensities of the two sources in the direction of the screen. This experiment and related ones can be readily adapted for use in a physical science course.[5,6]

The Vision Curve

When monochromatic light of fixed radiant power (in watts) enters the eye, different sensations of brightness are evoked, depending on the wavelength of the light. In 1924, visual photometry experiments comparing different wavelengths were carried out on 52 human observers at the National Bureau of Standards. These data were then combined with other world data and adopted by the CIE as the official vision curve, which is universally accepted to this day.[7,8] The curve, henceforth referred to as the $V(\lambda)$ function, is shown in Fig. 3. The function reaches a peak at 555 nm, in the yellow region of the spectrum, where the eye is most sensitive to brightness. This peak is normalized to a value of one. Blue light at 494 nm, for example,

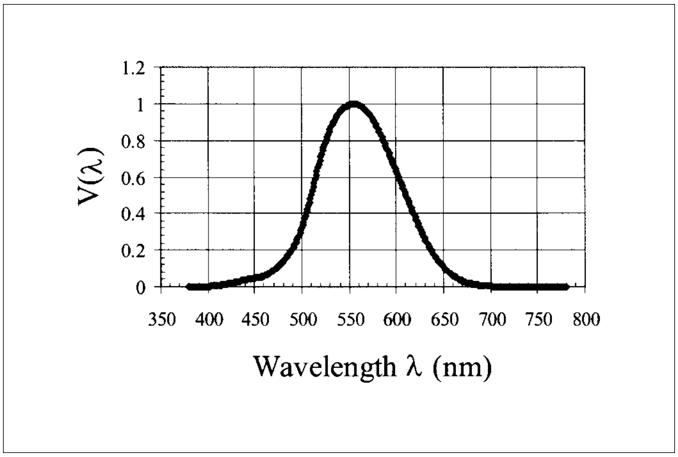

Fig. 3. Spectral sensitivity of the human eye. This curve was derived from experiments with human subjects in the 1920s. The peak, normalized to a value of one, occurs at 555 nm, where the eye is most sensitive to brightness.

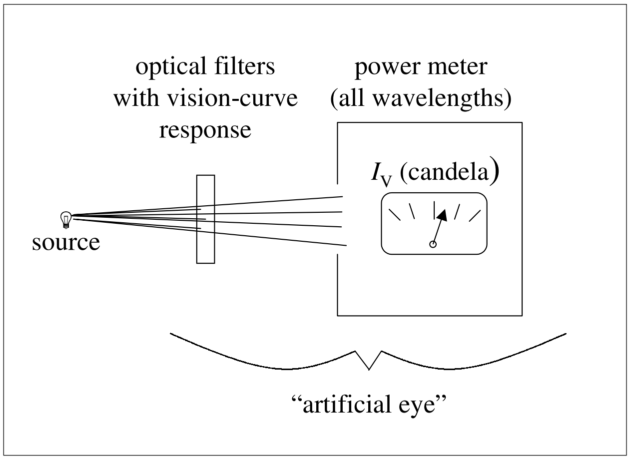

Fig. 4. The basic idea behind physical photometry. The filter transmits EM radiation according to the spectral sensitivity of the eye. The radiometer thus gauges the luminous properties of the source (as would be judged by a human).

has $V = 0.25$, meaning that four times as much (objective) radiant power is required to stimulate the same (subjective) perception of brightness as 555-nm light.

Physical Photometry: Determining the Luminous Intensity of a Light Source Using Objective Instruments

With the $V(\lambda)$ function accepted as the standard description of human visual response, photometric measurements could then proceed with *no further input from human observers*. Physical photometry uses optical filters and a radiometer (power meter) in place of the human eye. Figure 4 shows the basic idea. The optical filters are designed with a transmission spectrum that has the same shape as the vision curve. Only visible radiation reaches the radiometer, with different colors producing effects in proportion to their $V(\lambda)$ values. The total power, integrated over all wavelengths at the radiometer, is thus proportional to the brightness that would be sensed by a human observer. (The output of the radiometer could then be calibrated to read out photometric units such as candela.) The term "artificial eye," which appeared in the early literature, aptly describes this combination of filter and detector.[9,10] At the National Institute of Standards and Technology (NIST) in Maryland, elaborate networks of intercalibrated instruments achieve, in essence, an artificial eye.[11] An absolute measurement of incident power is accomplished with a High Accuracy Cryogenic Radiometer (HACR).[12] The incoming radiation is absorbed by the HACR's liquid-helium-cooled cavity, where it deposits thermal energy. The optical power is determined by the "electrical substitution" method, whereby the light is temporarily shuttered out and an equivalent thermal effect is brought about by the joule heating of a precision resistor. From I^2R of the resistor, the optical power is determined absolutely in watts.

In the 1970s, the instrumentation for performing physical photometry measurements became so precise that practical limitations of the candela's blackbody definition became evident. A *perfect* blackbody radiator is an idealization. In practice, different molten-platinum standards in different laboratories resulted in slight inconsistencies in the magnitude of the candela. In 1979, the CIPM (Comite International des Poids et Mesures, or International Committee on Weights and Measures) decided to abandon the blackbody-standard-source definition of the candela.

Present Definition of the Candela

If one looks up "candela" in a dictionary of physics, the following up-to-date definition will be found:[13]

> One candela is the luminous intensity in a given direction of a 540×10^{12}-Hz monochromatic source (555-nm wavelength in air) that emits 1/683 watt per steradian in that direction.

This new definition removes the candela's tie to any specific physical object. Each standardizing laboratory is faced with the challenge and freedom of realizing the above definition using its own set of absolute detectors (physical photometers of the character of Fig. 4). In essence, the definition has transformed from being *source-based* (e.g., molten platinum) to being *detector-based.*

The above boxed definition of the candela is incomplete, for it does not indicate how to deal with wavelengths other than 555 nm. For these other wavelengths, one must use the $V(\lambda)$ function (vision curve shown in Fig. 3) to modify the power required for one candela. Using the example of blue light at 494 nm, whose $V(\lambda)$ value is 0.25, four times as much radiant intensity (4/683 watts per steradian) are needed to obtain one candela. For a continuous-spectrum light source, the radiant intensity per unit wavelength $\frac{dI_{\text{rad}}}{d\lambda}$ must be weighted with the V(λ) function as follows to yield the correct number of candela:

$$I_V(\text{candela}) = 683\int_0^{\infty} \frac{dI_{\text{rad}}}{d\lambda} V(\lambda)\, d\lambda, \qquad (2)$$

where $\frac{dI_{\text{rad}}}{d\lambda}$ has units of watts per steradian per nm.

Since the $V(\lambda)$ function falls to zero outside of the visible spectrum, the limits of integration can be taken from 380 nm to 780 nm without incurring any significant error. Equation (2) quantifies how much a light source's spectrum and the vision curve overlap each other. Example spectra of household lightbulbs will be presented below.

The number 683 in Eq. (2), once referred to as the "mechanical equivalent of light," establishes a concrete link, *at 555 nm only*, between photometric units of intensity (candela) and radiometric units of intensity (watts per steradian). Each watt per steradian of 555-nm light yields 683 candela of luminous intensity. Back in the early 1900s, when photometric standards were less reliable, the accepted mechanical equivalent of light was smaller by several percent.[9] The figure of 683 is based on the official $V(\lambda)$ function and the requirement that the present candela be harmonized with its previous molten-platinum definition.

Relationship Between the Candela and the Lumen

As discussed in relation to Fig. 1, intensity quantifies (in watts per steradian) the concentration of radiated energy in a particular direction. Flux, on the other hand, quantifies (in watts) the overall energy radiated in all directions. Radiant flux concerns all wavelengths; luminous flux concerns only visible light. The symbol for luminous flux is Φ_V and its SI unit is the lumen (lm). If the luminous intensity (I_V) is known in every direction, it can be integrated over the entire sphere of solid angle to obtain the luminous flux Φ_V.

$$\Phi_V\,(\text{lumens}) = \int_{\Omega} I_V\,(\text{candela})\,d\Omega, \qquad (3)$$

where $d\Omega$ is an infinitesimal solid angle, and the integral is taken over the entire sphere of directions. The total solid angle subtended by a sphere is 4π. Hence for the special case of a point source that emits light uniformly in all directions, the relation between candela and lumens becomes simply

$$\Phi_V\,(\text{lumens}) = 4\pi \cdot I_V\,(\text{candela}). \qquad (4)$$

A one-candela uniform source emits 4π lumens of luminous flux.

In terms of units, 1 lumen = 1 candela × 1 steradian. Equation (2) can therefore be recast in terms of flux by multiplying both sides by one steradian, giving

$$\Phi_V\,(\text{lumens}) = 683\int_0^{\infty} \frac{d\Phi_{\text{rad}}}{d\lambda} V(\lambda)\, d\lambda, \qquad (5)$$

where $\frac{d\Phi_{\text{rad}}}{d\lambda}$ is radiant flux per unit wavelength (in watts per nm). A 555-nm source has $V(\lambda) = 1$ and hence would give off 683 lumens for each watt. The figure of 683 lm/W is the maximum theoretical conversion between power and luminous flux. At wavelengths other than 555 nm, owing to the eye's spectral sensitivity, the conversion from watts to lumens is reduced by a factor of $V(\lambda)$. Using 494-nm blue light [$V(\lambda) = 0.25$] for example, one obtains only 171 lm/W. *Luminous efficacy* is the term used for the watt-to-lumen conversion, equal to 683 lm/W × $V(\lambda)$.[14] Figure 5(a) plots the luminous efficacy of monochromatic radiation.

Incandescent Versus Fluorescent Lamps

Incandescent lightbulbs are very poor converters of electrical energy to luminous flux. The blackbody spectrum of a 60-W bulb[15] (filament temperature of 2800 K)[16] peaks in the infrared [see Fig. 5(b)]. With less than 10% of the radiated energy in the visible region, the efficacy is only about 14 lm/W. Lightbulb packaging, which lists both the electrical power in watts and the luminous flux in lumens, is a good source of data for student inquiries.[17]

Fluorescent lamps operate at low temperatures. Figure 5(c) shows a typical spectrum as measured by a CCD-based spectrophotometer (with some emission outside the visible region suppressed). The strong lines in the spectrum originate from the excited mercury vapor in the tube, while the continuum part of the spectrum is the radiation converted from UV to visible by the fluorescent coating on the inside surface of the bulb. Luminous efficacies of around 70 lm/W are typically achieved. Fluorescent tubes are hence five times as efficient as incandescent bulbs at producing the sensation of brightness. Some of the fluorescent lamp's spectral lines are located near the UV edge of the visible (365 nm), where the eye is hardly sensitive. There is also residual heat loss from the bulb. These two factors prevent fluorescent lamps from achieving the theoretical maximum of several hundred lumens per watt.

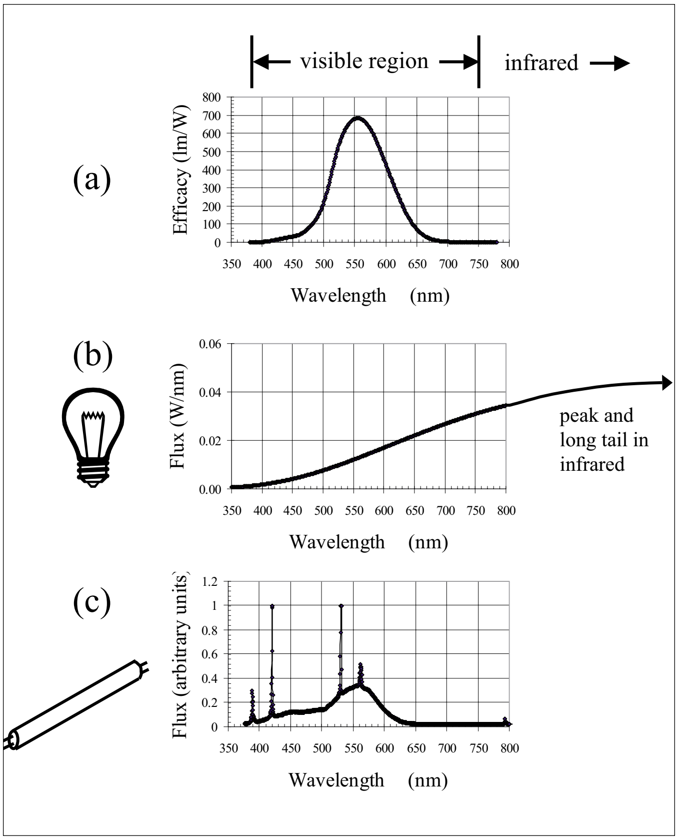

Fig. 5. (a) Efficacy is the conversion between watts and lumens. The peak occurs at 555 nm, for which 683 lumens are produced per watt of radiation. (b) Spectrum of a 60-W incandescent lightbulb (approximated as a 2800-K blackbody radiator). The spectrum peaks outside the visible region, causing the efficacy to be poor. (c) Spectrum of a "cool white" fluorescent lightbulb, as measured by a spectrophotometer (where some flux outside the visible region is suppressed). With its emission concentrated in the visible region, a fluorescent bulb achieves about five times the efficacy of an incandescent bulb.

The Anthropocentric Candela: Does It Deserve to be an SI Base Unit?

As a final note, I would like to pose an open question. *Does the candela belong with the ranks of the meter, kilogram, second, ampere, kelvin, and mole as a base unit?* To be sure, the candela is basic, in the sense that it cannot be replaced by any combination of other base units. (It must be recalled that the conversion between watts per steradian and candela is *wavelength dependent.*) The candela is also basic in that it provides the standardization for all other photometric units, such as the lumen, lux, lambert, etc.[18] The detracting side of the argument is that the candela is an anthropocentric unit. Whereas the meter, kilogram, second, etc. are defined with no reference to human observers, the candela attempts to measure *human-perceived* brightness. Subjective human data infects the candela through its reliance on the $V(\lambda)$ function, which comes from human-subject experiments of 1924. If the SI system is to encompass human vision, why not human hearing as well? The phon and the sone are units that deal with humans' spectral sensitivity to acoustic sensory input, but they are not SI base units.

The question of dropping the candela from the SI system has in fact been hotly debated at CIPM meetings. In the end, the long and distinguished history of photometric science is what has kept the candela in the flock.[19] After all, vision is our primary sense.

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