Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

No changes to the current definitions for the units of light

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Light

- Like fish that take water for granted, light is also often taken for granted.
- The reason: A network of international and national standards and norms that ensures that there is always enough light available to carry out the desired activity, especially at workplaces and in public spaces.
- To establish this network of standards, a common language regarding the units to be uses had to be developed.
- This is why a uniform system of units, such as the SI, becomes important.

SI

- SI: Backbone of an internationally agreed System of quantities considered important for education, science, industry, and trade.
- It is the common language required for the comparison of and between quantities and measurands.
- It was the final outcome of a process started with the Meter Convention to overcome the confusing variety of different measures of quantities.
- Continuous work over 80 years to find reliable artifacts for the quantities considered important in order to assign them **base units** that fulfill the boundary condition of a coherent system of units

SI

- The decision of the CGPM in 1954 to establish a **practical system of units** can be regarded as the birth of the SI. The quantities considered important were: time, length, mass, temperature, electrical current, luminous intensity (and amount of matter in 1971), with quantity values of the artefacts chosen to best fit their daily use in technology and society.

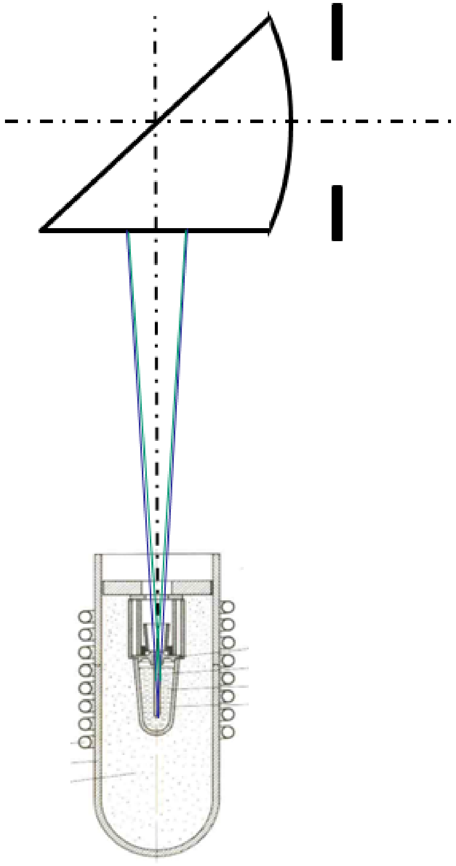
- Since 2019, a system of 7 defining constants **based on the quantity values of the artefact-based unit system** is used for the realization of all units of quantities within the SI, regardless of whether they are considered as so-called base or derived units.

Coherent system of units

Defining Constants	Symbol	SI coherent unit
hyperfine transition frequency of Cs	$\Delta\nu_{\mathrm{Cs}}$	$\mathrm{Hz}(=\mathrm{s}^{-1})$
speed of light in vacuums	c	$\mathrm{m\,s}^{-1}$
Planck constant	h	$\mathrm{Js}(=\mathrm{kg\,m}^2\mathrm{s}^{-1})$
luminous efficacy	K_{cd}	$\mathrm{lmW}^{-1}(=\mathrm{cd\,sr\,kg}^{-1}\mathrm{m}^{-2}\mathrm{s}^3)$
Boltzmann constant	k_{B}	$\mathrm{JK}^{-1}(=\mathrm{kg\,m}^2\mathrm{s}^2\mathrm{K}^{-1})$
elementary charge	e	$\mathrm{C}(=\mathrm{A\,s})$
Avogadro constant	N_{A}	mol^{-1}

	$\Delta\nu_{\mathrm{Cs}}$	c	h	K_{cd}	k_{B}	e	N_{A}
s	-1	-1	-1	3	2	1	
m		1	2	-2	2		
kg			1	-1	1		
cd				1			
K					-1		
A						1	
mol							-1

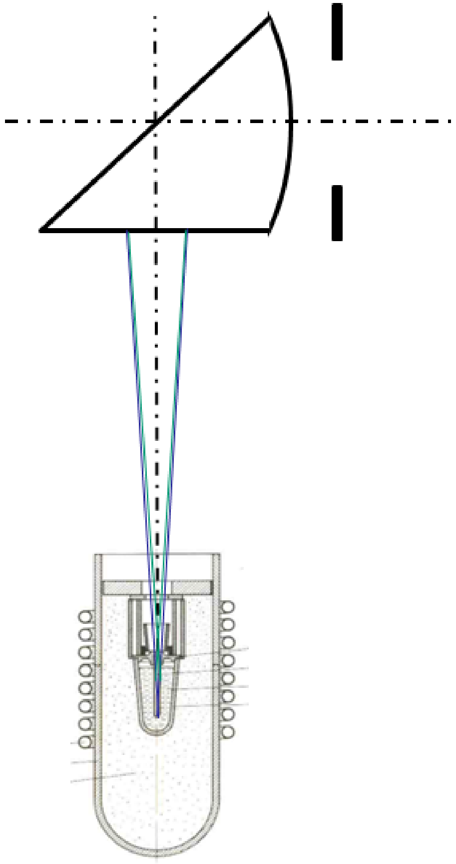
Photometric units



Luminous Intensity:

1967: The candela is the luminous intensity, in the perpendicular direction, of a surface of 1/600000 square metre of a black body at the temperature of freezing platinum under a pressure of 101 325 newtons per square metre.

Photometric units

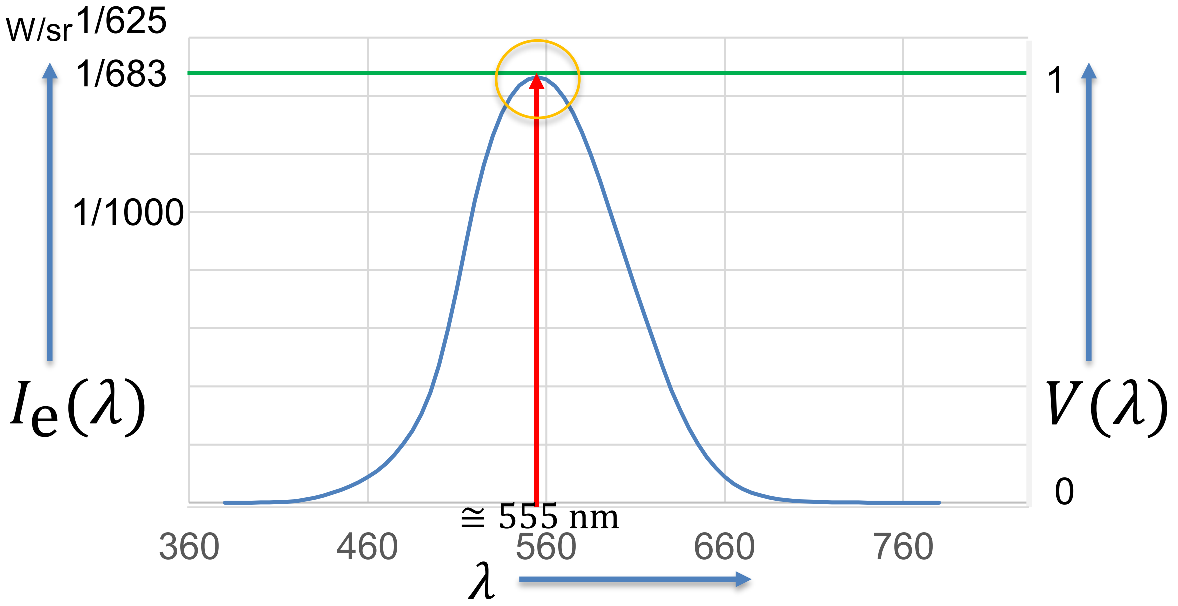


Luminous Intensity:

1967: The candela is the luminous intensity, in the perpendicular direction, of a surface of 1/600000 square metre of a black body at the temperature of freezing platinum under a pressure of 101 325 newtons per square metre.

1979: The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 × 10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.

misleading



$$I_V = K_m \int_{360}^{830} I_e(\lambda) V(\lambda) \mathrm{d}\lambda$$

max luminous efficacy

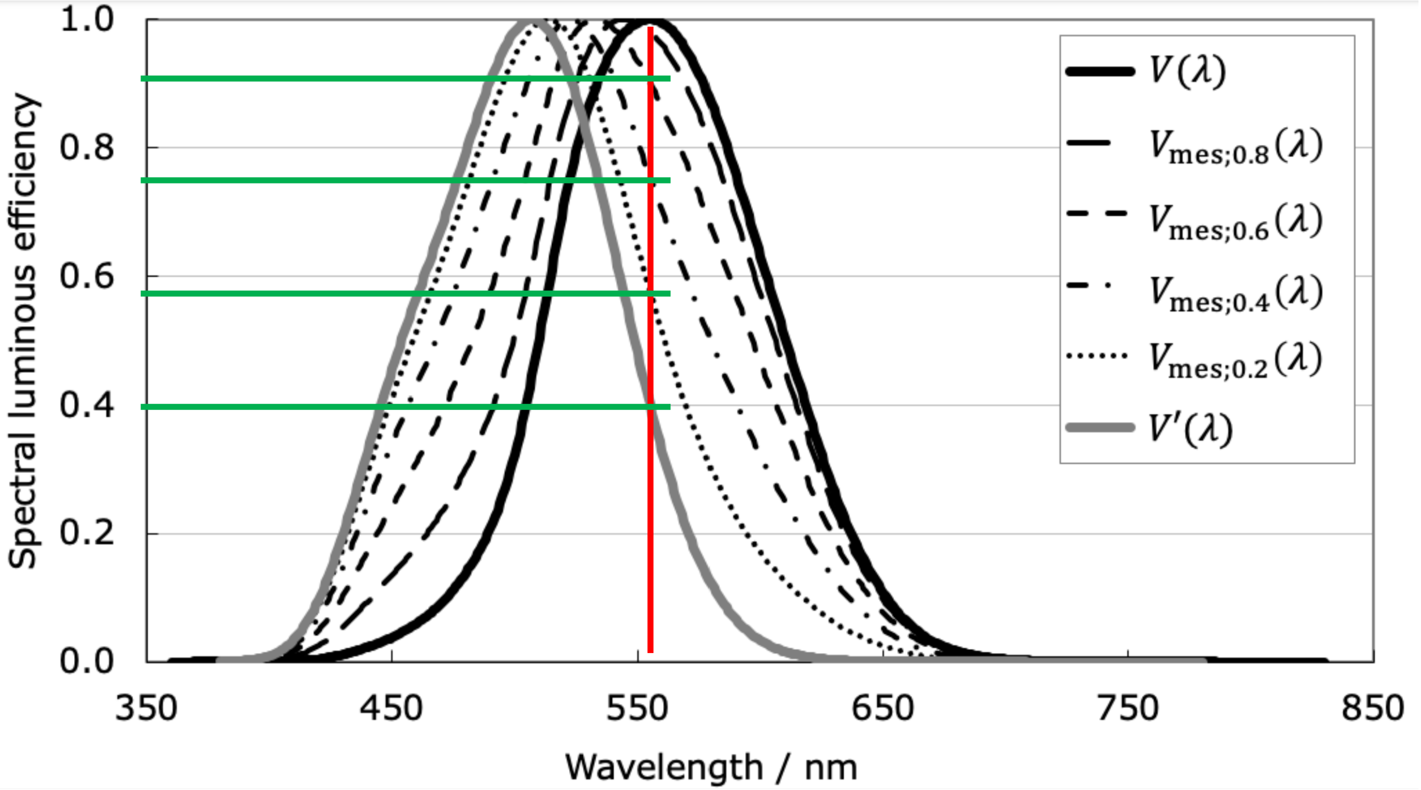
Photometric units

- Luminous efficacy K_{cd}

2019: The luminous efficacy of monochromatic radiation of frequency $540 \cdot 10^{12}$ Hz, K_{cd}, is 683 lmW^{-1}

$$I_V = \frac{K_{\text{cd}}}{V_x(\lambda_{\text{cd}})} \int_{360}^{830} I_{\text{e}}(\lambda) V_x(\lambda) \text{d}\lambda$$

max luminous efficacy



- for the luminous intensity, cd, it follows:

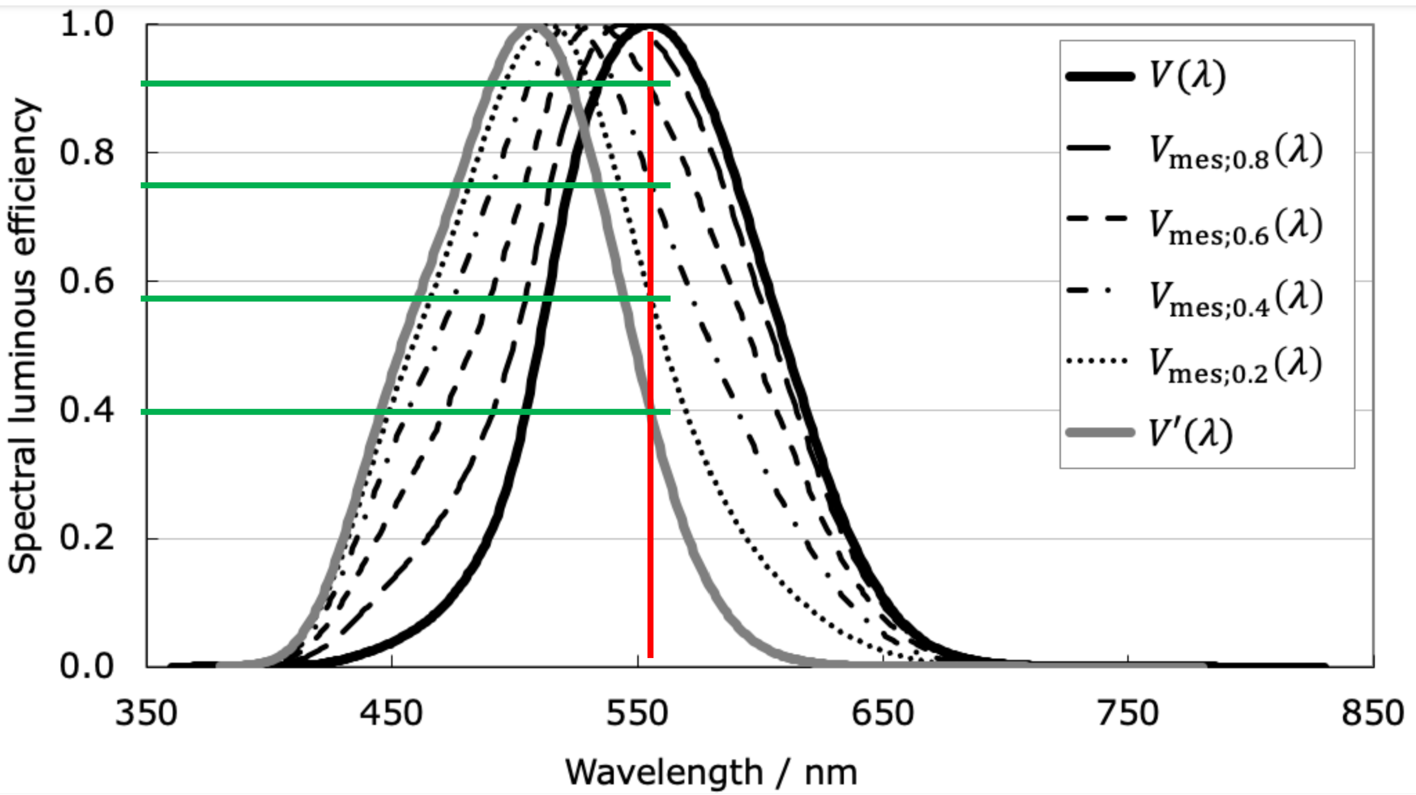
The candela, symbol cd, is the SI unit of luminous intensity in a given direction. It is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of the frequency $540 \cdot 10^{12}$Hz, K_{cd}, to be 683 when expressed in the unit lm W^{-1}, which is equal to cd sr W^{-1}, or cd sr kg^{-1}m^{-2}s^{3}, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{\text{Cs}}$.

Photometric units

- Luminous efficacy K_{cd}

2019: The luminous efficacy of monochromatic radiation of frequency $540 \cdot 10^{12}$ Hz, K_{cd}, is 683 lmW^{-1}

$$I_V = \frac{K_{\mathrm{cd}}}{V_x(\lambda_{\mathrm{cd}})} \int_{360}^{830} I_{\mathrm{e}}(\lambda) V_x(\lambda) \mathrm{d}\lambda$$



$$\Phi_V = \frac{K_{\mathrm{cd}}}{V_x(\lambda_{\mathrm{cd}})} \int_{360}^{830} \Phi_{\mathrm{e}}(\lambda) V_x(\lambda) \mathrm{d}\lambda$$

$$E_V = \frac{K_{\mathrm{cd}}}{V_x(\lambda_{\mathrm{cd}})} \int_{360}^{830} E_{\mathrm{e}}(\lambda) V_x(\lambda) \mathrm{d}\lambda$$

$$L_V = \frac{K_{\mathrm{cd}}}{V_x(\lambda_{\mathrm{cd}})} \int_{360}^{830} L_{\mathrm{e}}(\lambda) V_x(\lambda) \mathrm{d}\lambda$$

How to distinguish photometric quantities

„Mise en pratique“ for the definition of the candela:

Chapter 3.1

… the International Commission on Illumination (**CIE**) **has defined** a set of spectral weighting functions or action spectra, referred to as **spectral luminous efficiency functions** that describe the relative spectral sensitivity of the average human eye **for specified visual conditions**.

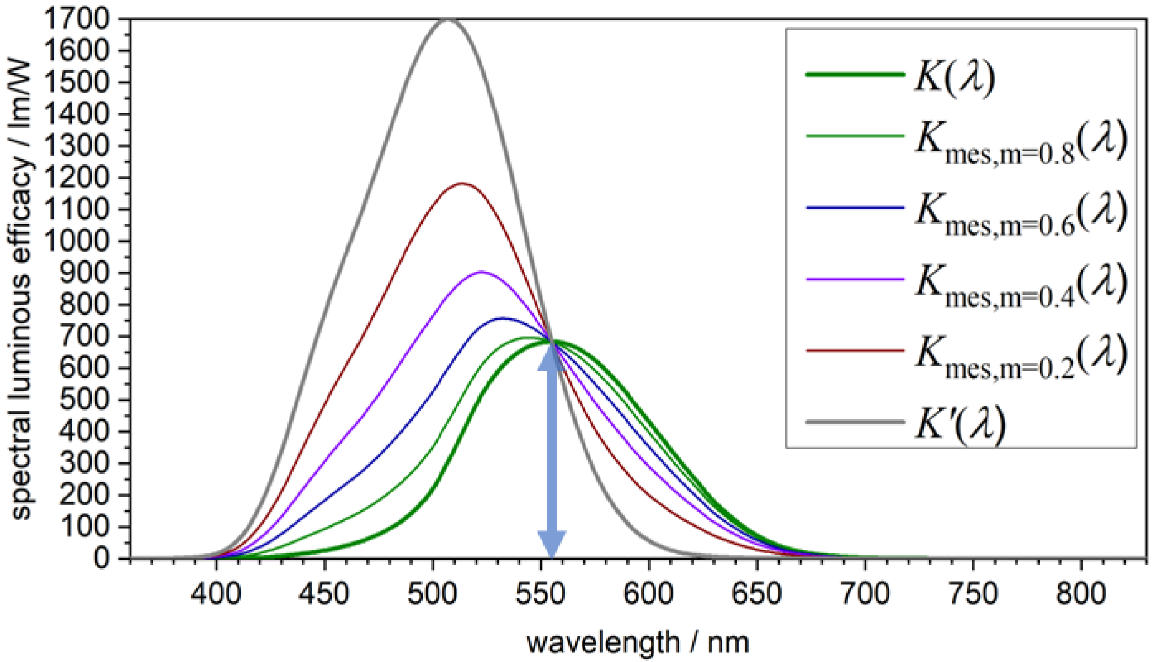
…The constant, K_{cd} , together with the spectral luminous efficiency functions, relates photometric quantities and radiometric quantities to establish a metrologically consistent system

How to distinguish photometric quantities

BIPM: Principles Governing Photometry, 2nd Edition, (Rapport BIPM-2019/05)

Chapter 5 gives advises how to name quantities and symbols

- If no additional information is provided, it is assumed that the classic photometric 2°-Observer is meant
  - photopic luminous flux, Φ_V → luminous flux, Φ
  - …
- In all other cases the description of the field of application must be added:
  - → mesopic luminous flux, $\Phi_{\mathrm{mes};m}$
  - → scotopic luminous flux, Φ'
  - → 10°luminous flux, Φ_{10}



New luminous efficiency functions

BIPM: Principles Governing Photometry, 2nd Edition, (Rapport BIPM-2019/05)

….

For research purposes, photometric quantities for observers other than those introduced … above … may be used, e.g. the CIE 2015 physiologically-based spectral luminous efficiency function …, and the CIE 1988 modified 2° observer … . When one of these alternative CIE-defined observers is used, an appropriate quantity name (e.g. CIE 2015 luminous flux, or CIE 1988 luminous flux), and an appropriate symbol for the quantities (e.g. Φ_{F} or Φ_{M}) should be used to avoid any confusion with other CIE-defined photometric quantities. ….

….For non-visual effects radiometric units are used.

Conclusion

- The current SI fully meets the requirements of a practicable system of units for education, science, industry and trade.
- In contrast to the definition of luminous intensity by a monochromatic radiant intensity, the current definition of K_{cd} significantly improves the understanding of the definition.
- The current „mise en pratique“ and the 2nd edition of the monography „Principles Governing Photometry“ already describe how to handle other and new types of observers.
- It makes no sense to redefine K_{cd} to prevent a change in the measured values when transitioning to cone fundamental observers as long as $V(\lambda)$ lies within the set of cone fundamentals generated by age, ethnicity and gender dependence.

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