

A Dilettante's View of the Candela in the International System of Units*

John Lehman
Alan Migdall
Julia Scherschligt
Lorne Whitehead

Dilettante: from Oxford Languages (WWW):

“a person who cultivates an area of interest, [...] such as the arts, without real commitment or knowledge”

I will end where I started:

“Why is the candela a base unit in the SI?”

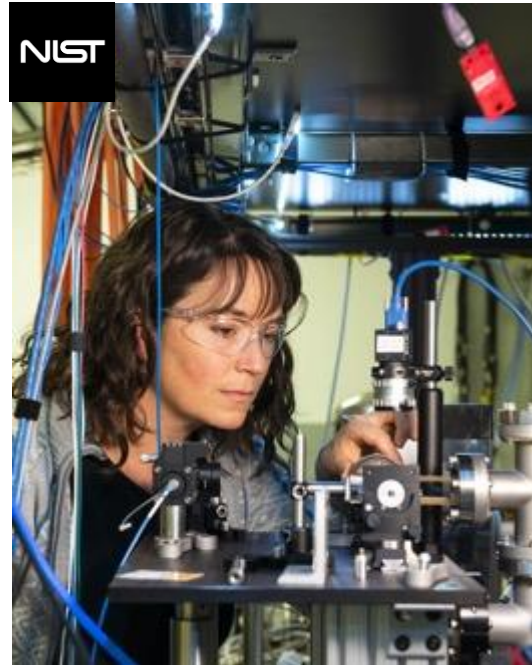
Who we are

Alan Migdall



Quantum Optics Group of the Quantum Measurement Division & Fellow of the Joint Quantum Institute, the American Physical Society, and Optica

Julia Scherschligt



Calls her group the “custodians of temperature and pressure” in the US

Consultative Committee for Mass and Related Quantities (CCM-WGPV)

Lorne Whitehead



Chair CIE Technical Committee 1-98 “A roadmap toward basing CIE colorimetry on cone fundamentals”.

UBC Professor • former Provost, 140 patents • six companies (displays and lighting)

OPEN ACCESS

IOP Publishing | Bureau International des Poids et Mesures

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Letter to the Editor

A proposal for three categories of units within the SI

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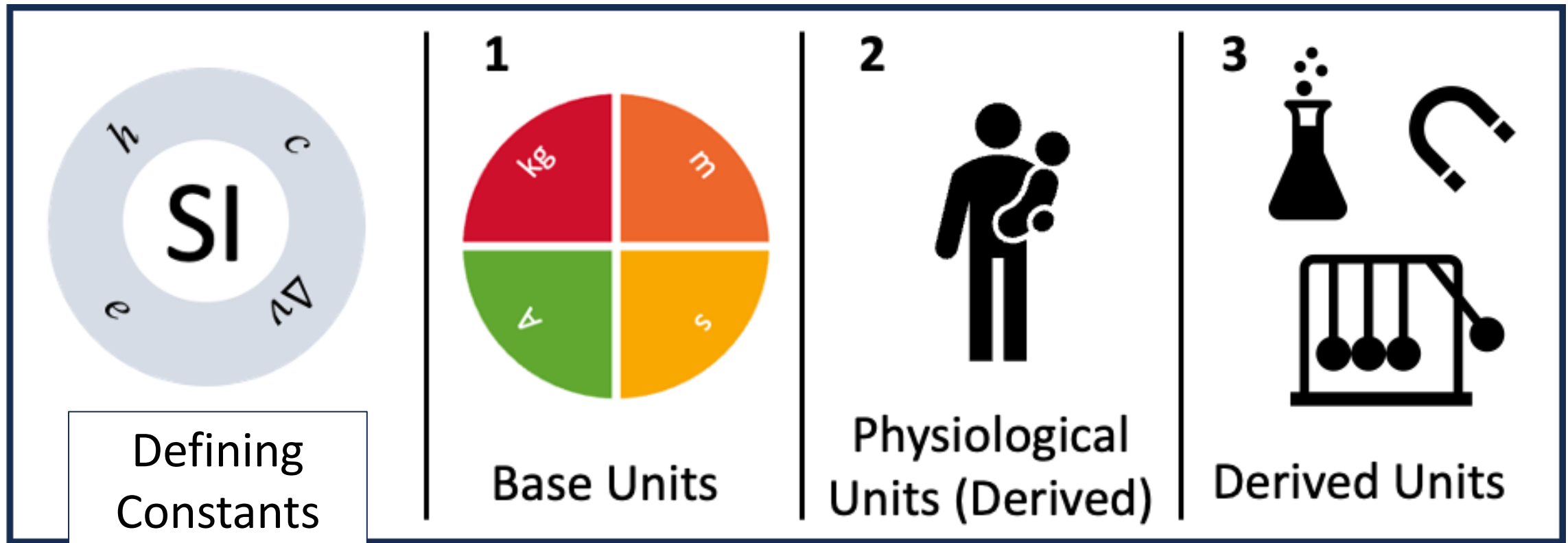
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[/1681-7575/ad57cc](https://doi.org/10.1088/1681-7575/ad57cc)

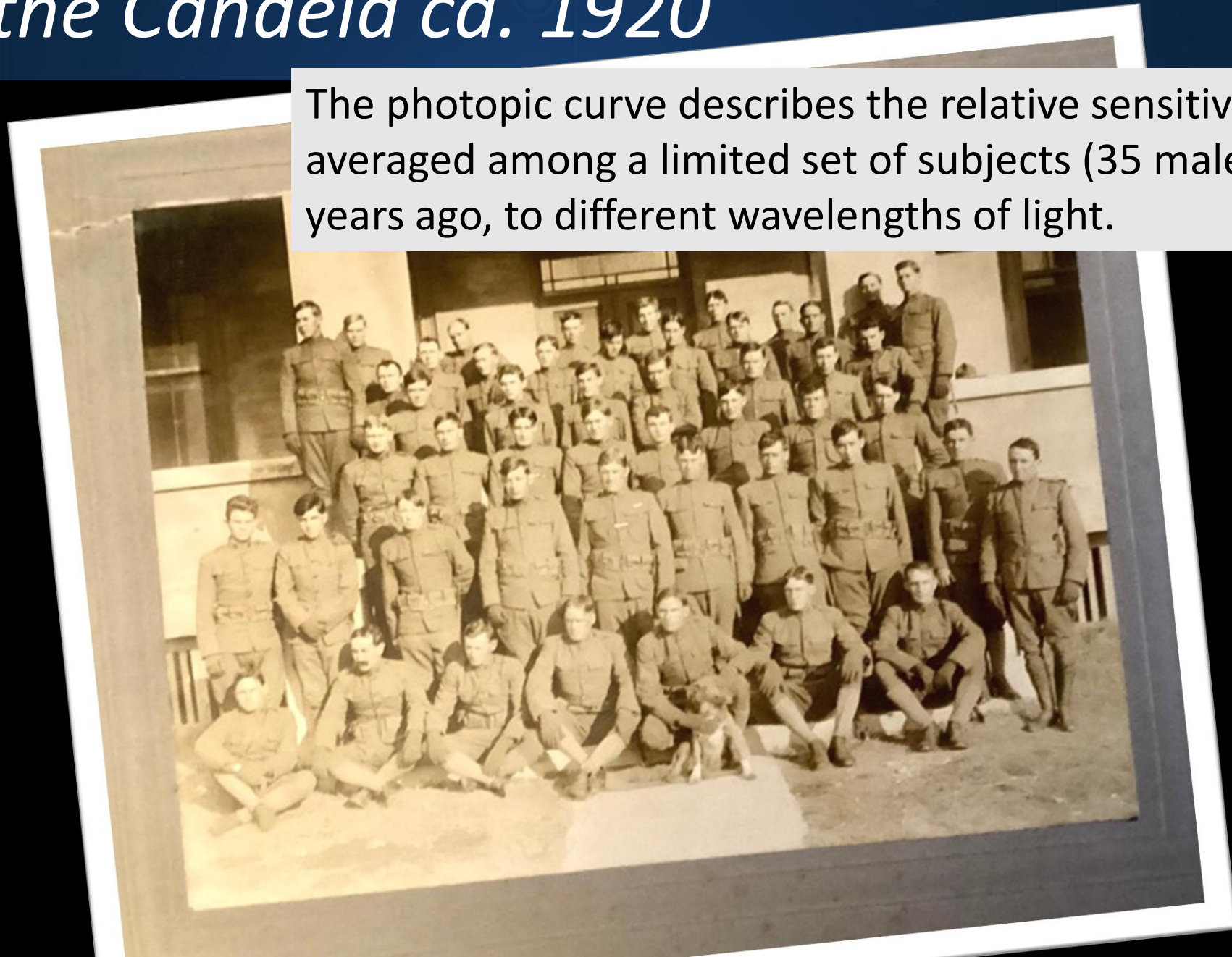
Corrigendum: Corrections to a proposal for three categories of units within the SI (2024 Metrologia 61 033001)

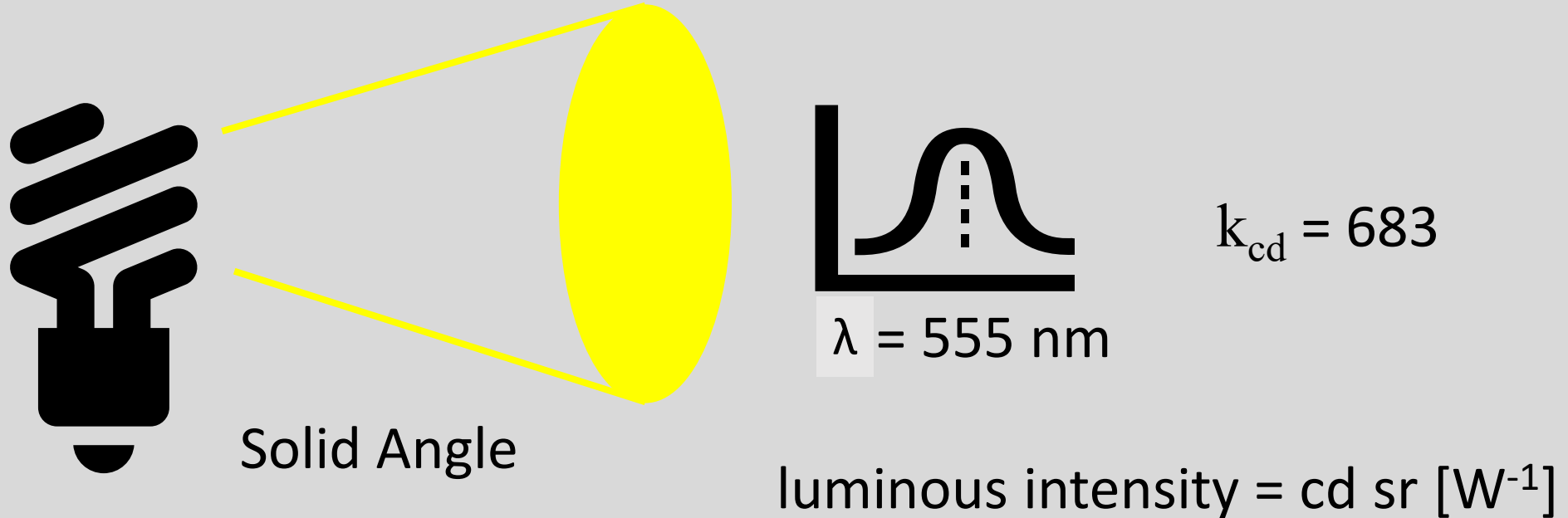


1. Intro
2. What is the 2019 SI?
3. What should the SI look like?
4. Proposal

the Candela ca. 1920

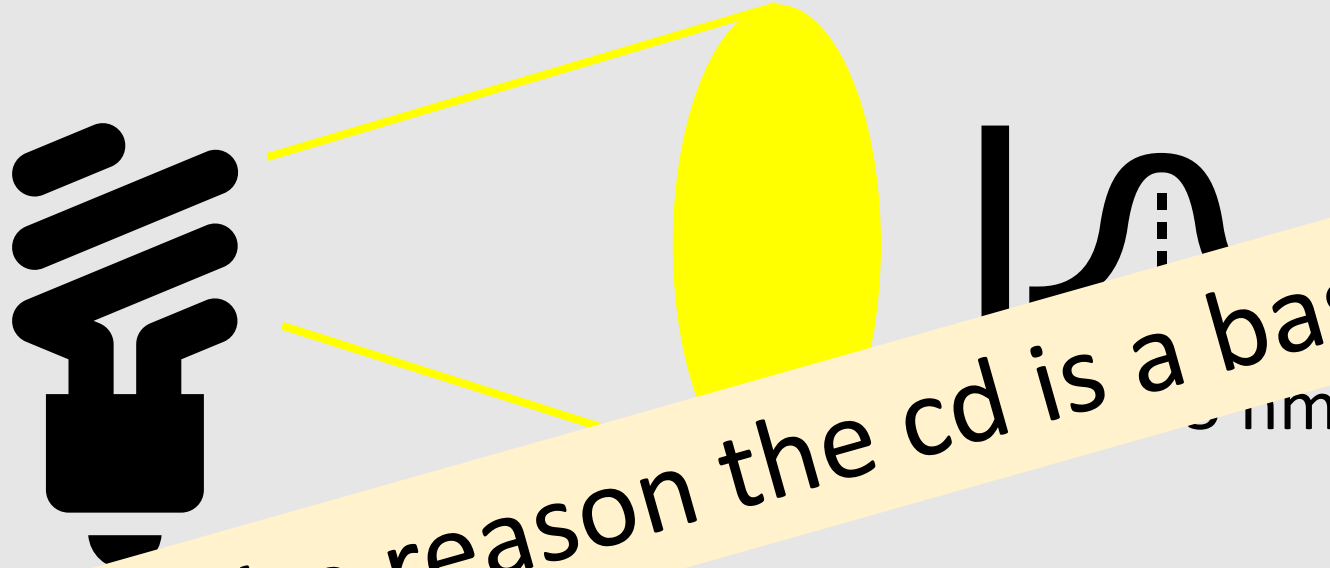
The photopic curve describes the relative sensitivity of the human eye, averaged among a limited set of subjects (35 male, 5 female), ca. 100 years ago, to different wavelengths of light.





- Luminous intensity is **wavelength-weighted** optical power in a particular direction per solid angle.
- The wavelength-weighting is based on CIE's luminosity function, but it is specified at a center wavelength (555 nm)

2023: LED LIGHTING IS \$80B INDUSTRY

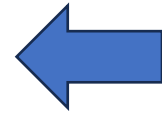


This is the reason the cd is a base unit!

- Luminous intensity is wavelength-weighted optical power in a particular direction per solid angle.
- The wavelength-weighting is based on CIE's luminosity function, but it is specified at a center wavelength (555 nm)

Timeline of the SI

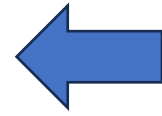
Year	change	note	Base Units
1790	m, kg	The French metric system	2
1889			
1954			
1960			
1970			
2018			



“For all Times and For all People”

Timeline of the SI

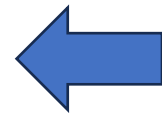
Year	change/addition	note	Base Units
1790	m, kg	The French metric system	2
1889	s	The "MKS" system	3
1954			
1960			
1970			
2018			



“For all Times and For all People”

Timeline of the SI

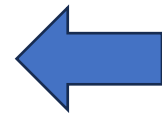
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1970	mol	The "Old SI"	7

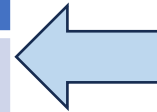
← "For all Times and For all People"

a "lengthy discussion"
[SI Brochure, appendix 4, part 2].

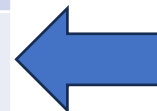
← *& minutes of the 1971 BIPM/CGPM meeting*

Timeline of the SI

Year	change/addition	note	Base Units
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1889	s	The "MKS" system	3
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1960	cd, K	The "International System" (SI)	6
1970	mol	The "Old SI"	7
2018	7 exact constants	The "New SI"	7

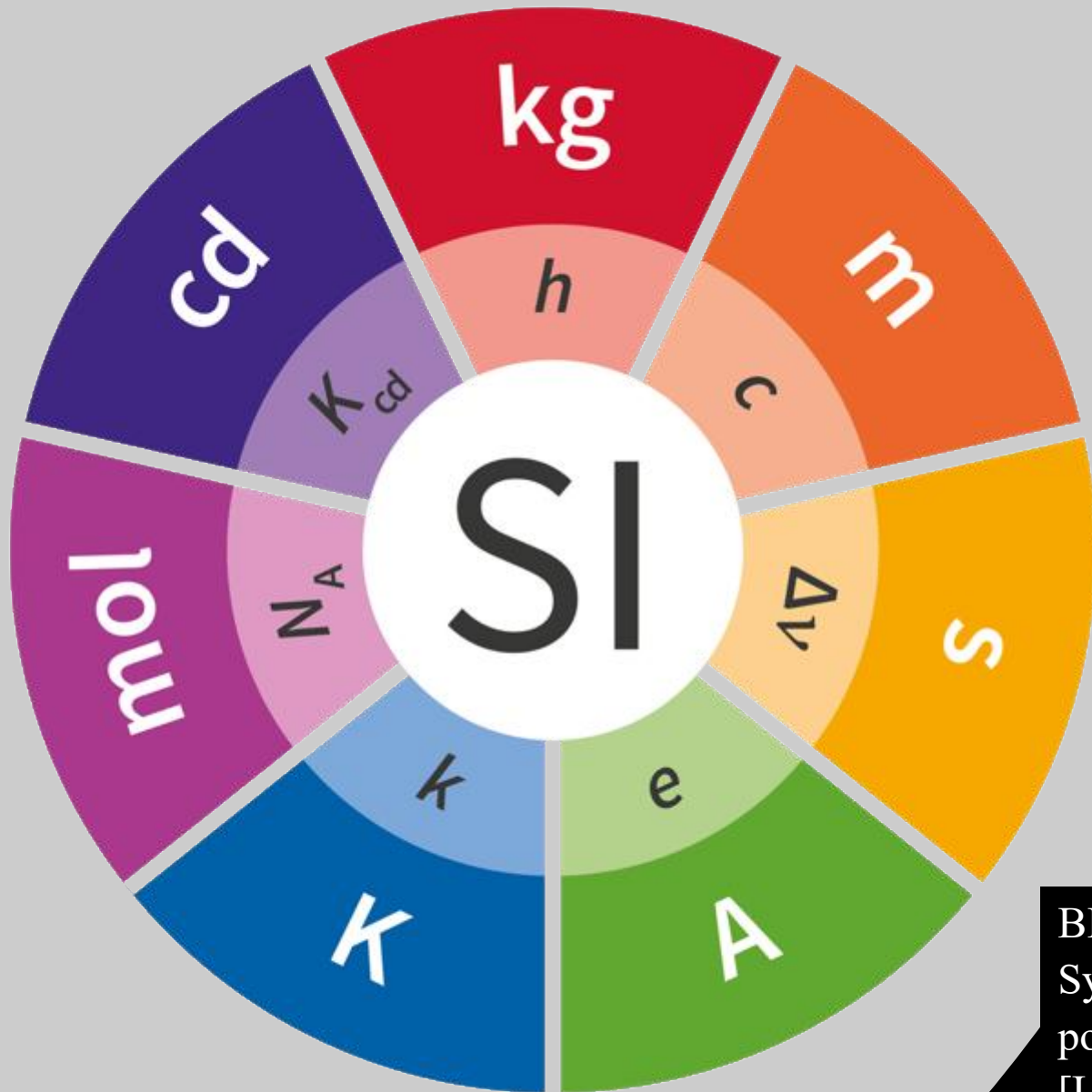


"For all Times and For all People"



2019 SI Brochure -- Uniform and Accessible for:

- international trade
- high-technology manufacturing
- human health and safety
- protection of the environment
- global climate studies
- and the basic sciences



2019 SI

7 base units

22 derived units

BIPM. Le Système international d'unités / The International System of Units ('The SI Brochure'). Bureau international des poids et mesures, ninth edition, 2019.

[URL http://www.bipm.org/en/si/si_brochure/, ISBN 978-92-822-2272-0].

What is the 2019 SI?

The numerical values of the seven defining constants have no uncertainty.

The definitions of the **base units** specify the exact numerical value of **each constant** when its value is expressed in the **corresponding SI unit**.

All units of the SI can be written either through a defining constant itself, or through products or quotients of the defining constants.

What is the 2019 SI?

1. The SI Brochure (rev 9) says: *The distinction between Base and Derived Units is not needed.*



What is the 2019 SI?

1. The SI Brochure (rev 9) says: *The distinction between Base and Derived Units is not needed.*
2. But SI Brochure says, *“Nevertheless, the concept of base and derived units is maintained because it is useful and historically well established, noting also that the ISO/IEC 80000 series of Standards specify base and derived quantities which necessarily correspond to the SI base and derived units defined here”*

International System of *Quantities* (not Units)

*“It is convenient to consider some quantities of different kinds as **mutually independent**. Such quantities are called **base** quantities. Other quantities, called **derived** quantities, are defined or expressed in terms of base quantities by means of equations.”*

The candela unit (and luminous intensity quantity), requires a watt, having units of $\text{kg}\cdot\text{m}^2\cdot\text{s}^{-3}$ and is *derived* from the kg, m, and second (quantities; mass, length, and time).

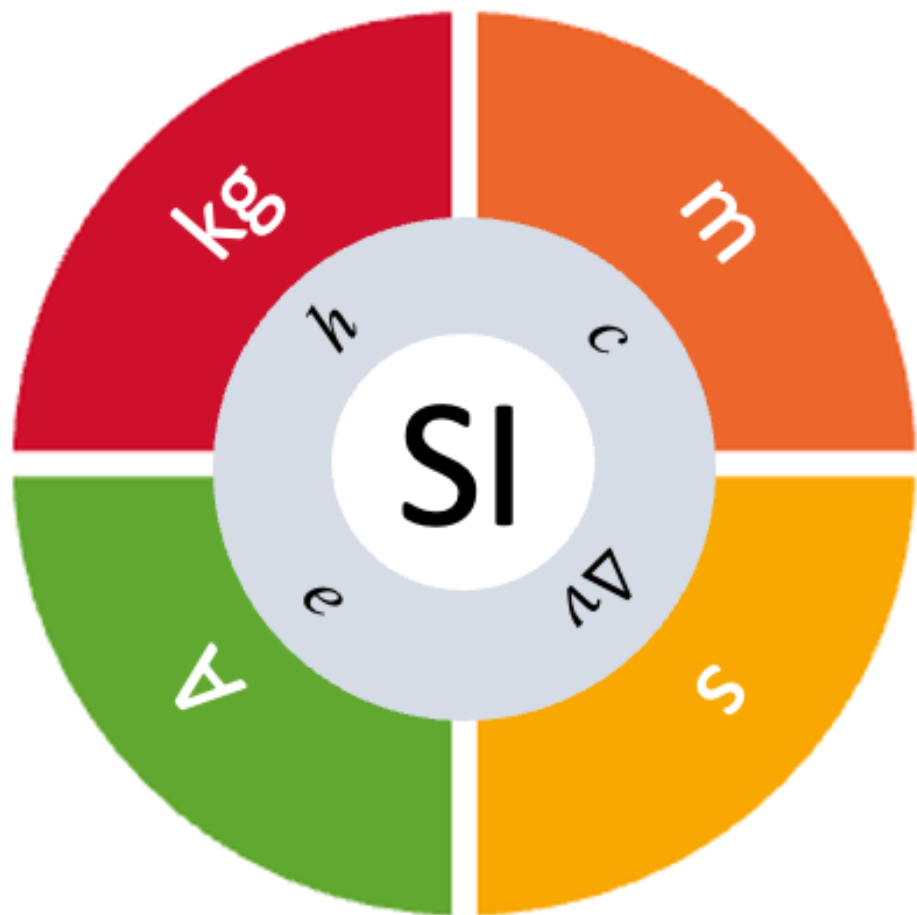
$$\text{luminous intensity} = \text{constant} [\text{kg}^{-1}] [\text{m}^{-2}] [\text{s}^{-3}]$$

$$\text{alternatively, cd} = \text{constant} \{h\}^{-1} \{\Delta\nu_{\text{cs}}\}^1$$

Only four units that are mutually independent (meter, kilogram, second, mol)(?)

Q: What is the minimum *basis* set to *derive* everything else?

(in other words, what ***should*** the SI look like?)



What if?

What is the 2019 SI?

All units of the SI can be written either through a defining constant itself, or through products or quotients of the defining constants.

$$\begin{aligned} \text{kg} &= [h]^1 [c]^{-2} [\Delta\nu_{\text{Cs}}]^1 [e]^0 \\ \text{m} &= [h]^0 [c]^1 [\Delta\nu_{\text{Cs}}]^{-1} [e]^0 \\ \text{s} &= [h]^0 [c]^0 [\Delta\nu_{\text{Cs}}]^{-1} [e]^0 \\ \text{A} &= [h]^0 [c]^0 [\Delta\nu_{\text{Cs}}]^1 [e]^1 \end{aligned}$$

Base Units

$$Q = \{Q\}[Q]$$

A =

Defining Constant	Dimensionality			
	kg	m	s	A
Δv_{Cs}	0	0	-1	0
c	0	1	-1	0
h	1	2	-1	0
e	0	0	1	1

$$\{\text{Constant}\} = (\text{number})[\text{kg}^a][\text{m}^b][\text{s}^c][\text{A}^d]$$

$A^{-1} =$

Unit	Dimensionality			
	Δv_{Cs}	c	h	e
kg	1	-2	1	0
m	-1	1	0	0
s	-1	0	0	0
A	1	0	1	1

$$[\text{Unit}] = (\text{number})\{h^a\}\{c^b\}\{\Delta v_{Cs}^c\}\{e^d\}$$

Base Units

$$Q = \{Q\}[Q]$$

The system is coherent

- See Richard Davis*

This form is non-degenerate

- non-zero determinate
- invertible

Can be used to define everything else

A =

Defining Constant	Dimensionality			
	kg	m	s	A
Δv_{Cs}	0	0	-1	0
c	0	1	-1	0
h	1	2	-1	0
e	0	0	1	1

A⁻¹ =

Unit	Dimensionality			
	Δv_{Cs}	c	h	e
kg	1	-2	1	0
m	-1	1	0	0
s	-1	0	0	0
A	1	0	1	1

$$\begin{aligned} \text{kg} &= [h]^1 [c]^{-2} [\Delta v_{Cs}]^1 [e]^0 \\ \text{m} &= [h]^0 [c]^1 [\Delta v_{Cs}]^{-1} [e]^0 \\ \text{s} &= [h]^0 [c]^0 [\Delta v_{Cs}]^{-1} [e]^0 \\ \text{A} &= [h]^0 [c]^0 [\Delta v_{Cs}]^1 [e]^1 \end{aligned}$$

$$\begin{aligned} [h] &= \text{kg}^1 \text{m}^2 \text{s}^{-1} \text{A}^0 \\ [c] &= \text{kg}^0 \text{m}^1 \text{s}^{-1} \text{A}^0 \\ [\Delta v_{Cs}] &= \text{kg}^0 \text{m}^0 \text{s}^{-1} \text{A}^0 \\ [e] &= \text{kg}^0 \text{m}^0 \text{s}^1 \text{A}^1 \end{aligned}$$

Defining Constant	Dimensionality		
	cd	mol	K
k	0	0	-1
N_A	0	-1	0
$K_{cd@555nm}$	0	0	0

“Scaling Factors”

$$cd = \text{constant} \{h\}^{-1} \{\Delta v_{cs}\}^1$$

Indeed Mutually Independent while the others are NOT(!!?)

One More Thing...

Specifically, an *operational, experimental* procedure must be used to *convert* the SI information about kg, m, s, A into *physical* standards.

Realization by “mise en pratique.”

(we don't really realize an Amp!)

What do we want! When do we want it!

NIST



<https://qz.com/966436/march-for-science-the-best-signs-from-protests-around-the->

We are not alone

“it seems sensible to retain the distinction between SI base units and SI derived units into the future.” (the SI brochure does not! or does it?)

Richard Brown, NPL Fellow, Metrologia 61 2024.

“[...] the number of naturally independent quantities, and hence the minimum number of base quantities within a unit system, is five. These can be, for example, mass, charge, length, time, and angle.”

Quincey and Burrows, Metrologia 56 2019

“a modified system of SI units is described that includes [...] “physiological units”. [...] special class of derived units that are defined with respect to specified reference stimuli for the purpose of calibrating the nominal human response to external physical effects.”

Nelson and Ruby, Metrologia 30 1993

What do we want! When do we want it!

1. *“The distinction between the **four** base and derived units **is** fundamental.”*
 - *or: get rid of modifiers (just constants and units)*
2. *CCPR SP resolution to have a conversation?*
 - *clarity, simplicity, pedagogy*
 - *define mutually independent (or get rid of it)*

END



We ask, why is the candela given the distinction of being a base unit in the International System of Units (SI)? What is a base unit?

Section 2.3 of the SI Brochure: the distinction between base and derived units is not needed, but “[...] the concept of base and derived units is maintained because it is useful and historically well established, noting also that the ISO/IEC 80000 series of Standards specify base and derived quantities which **necessarily correspond to the SI base and derived units** defined here.”

Section 4.2 of ISO80000: “It is convenient to consider some quantities of different kinds as **mutually independent**. Such quantities are called base quantities. Other quantities, called derived quantities, are defined or expressed in terms of base quantities by means of equations.”

If SI base units correspond logically to ISO base quantities, then SI base units are (must be?) mutually independent. But there are only four units that are mutually independent (meter, kilogram, second, mol). The candela, for example requires a watt (having units of $\text{kg}\cdot\text{m}^2\cdot\text{s}^{-3}$) and is *derived* from the kg, m, and second.