Candela in the Wind: A Proposal for Three Categories of Units Within the SI

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Lorne Whitehead

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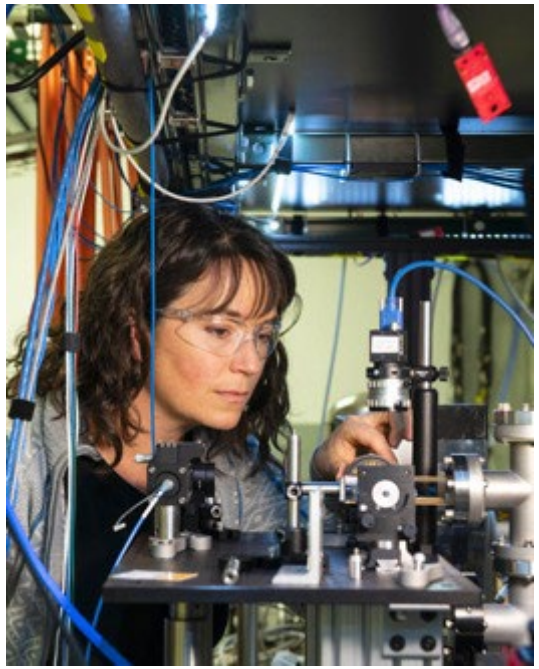
U.S. Department of Commerce

Who we are

Alan Migdall, NIST

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

Julia Scherschligt, NIST



Calls her group the "custodians of temperature and pressure" in the US

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

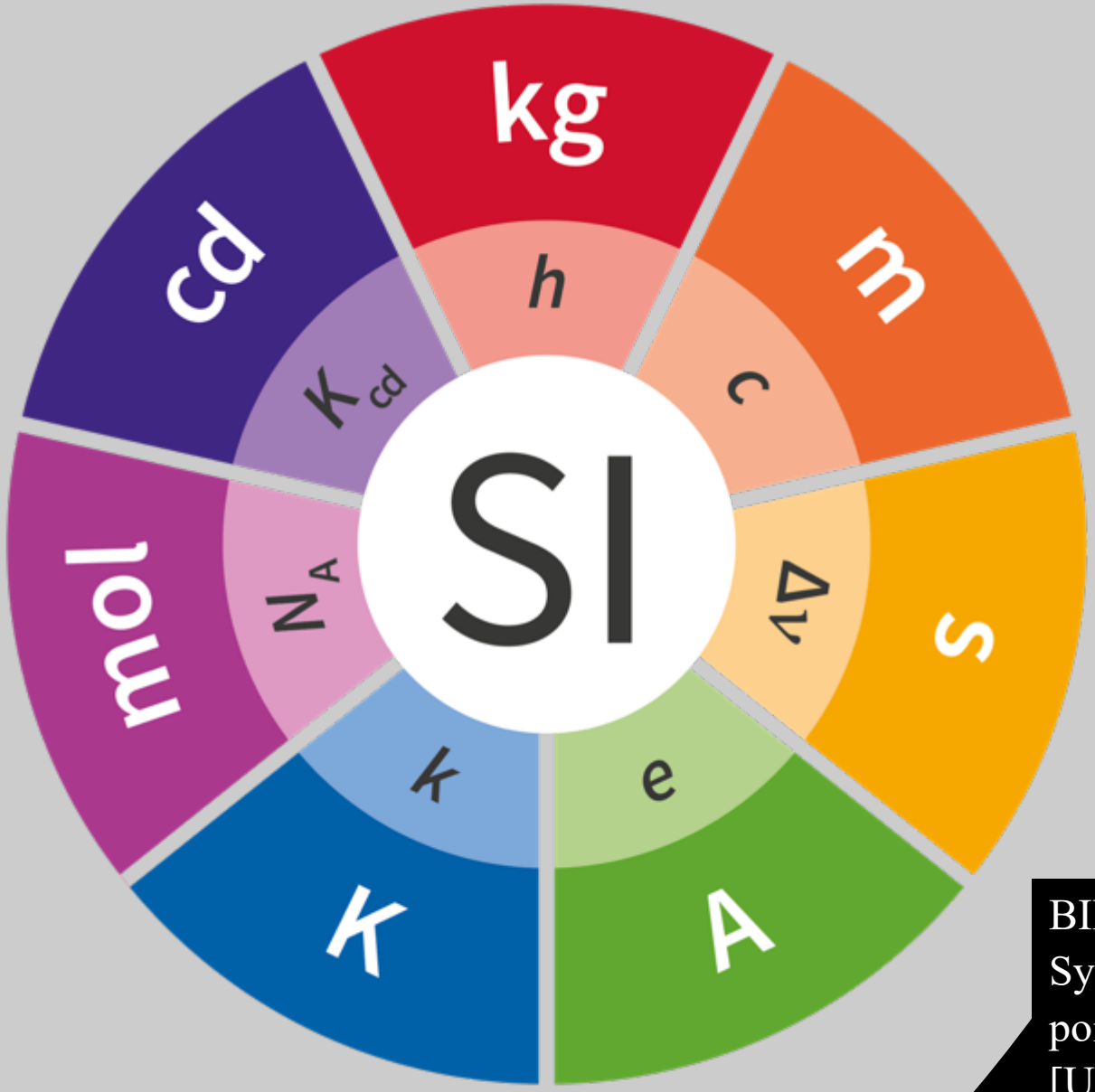
Lorne Whitehead, UBC

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), and much more!

Outline

1. Intro
2. What is the 2019 SI?
3. Why I am not indifferent
4. What should the SI look like? (the base units)
5. Short Shallow Dive
6. Proposal



2019 SI Brochure

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 SI is defined in terms of a set of seven defining constants. The complete system of units can be derived from the fixed values of these defining constants, expressed in the units of the SI.

The seven defining constants are:

- the caesium hyperfine frequency $\Delta\nu_{Cs}$
- the speed of light in vacuum c
- the Planck constant h
- the elementary charge e
- the Boltzmann constant k
- the Avogadro constant N_A, and
- the luminous efficacy of a defined visible radiation K_{cd}

https://www.bipm.org/en/measurement-units/si-defining-constants

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.

https://www.bipm.org/en/measurement-units/si-defining-constants

What is the 2019 SI?

1. The SI Brochure explicitly says there *no distinction between Base and Derived Units*!?

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*

https://www.bipm.org/en/measurement-units/si-defining-constants

What is the 2019 SI?

Resolution 1 of the 26th meeting of the CGPM

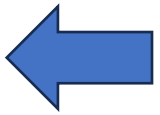
1. Is it enough units were “abrogated”?

2. "Appendix 3: the base units of the SI"

https://www.bipm.org/en/measurement-units/si-defining-constants

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

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1954			
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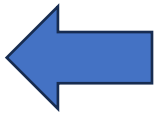

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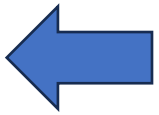
1960			
1970			
2018			



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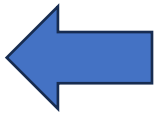
1970			
2018			



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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].

Timeline of the SI

Year	change/addition	note	Base Units
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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

The New-new SI

The New-New SI ca. 2030?

1. Proposed redefinition of the second:
Demarcq N et. al Metrologia 2024 61012001 (1-19). doi: 10.1088/1681-7575/ad17d2.1

2. Possible, proposed redefinition of the candela:
CCPR-WG-SP The Future of the Candela, BIPM, Paris, June 2024

3. Unitless dimensions: Radian
Mohr P J, and Phillips W D, 2015 52 40-47. doi:10.1088/0026-1394/52/1/40.

4. (but the SI Brochure can be updated periodically)

Where is optical Power?

(why am I not impartial?)

Mass and Force

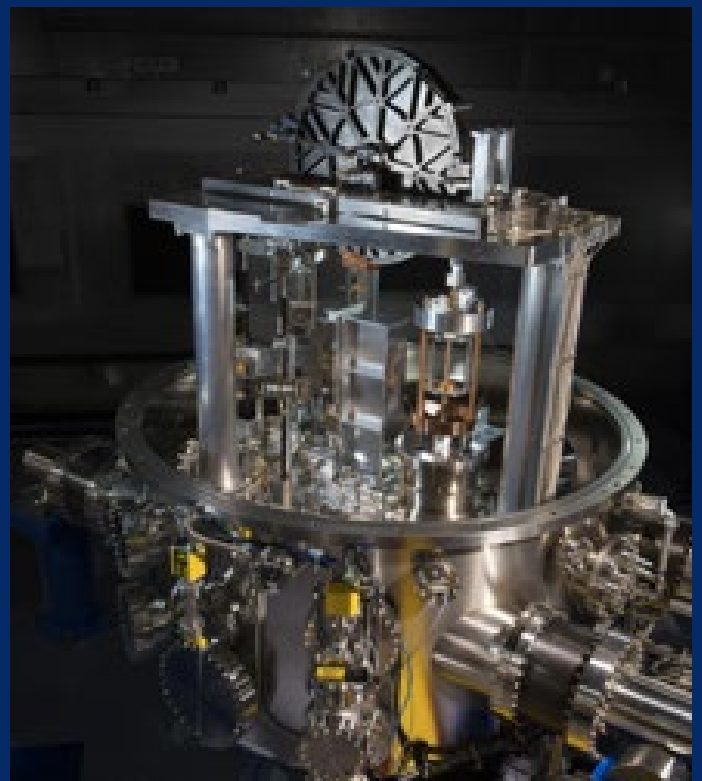
The new SI

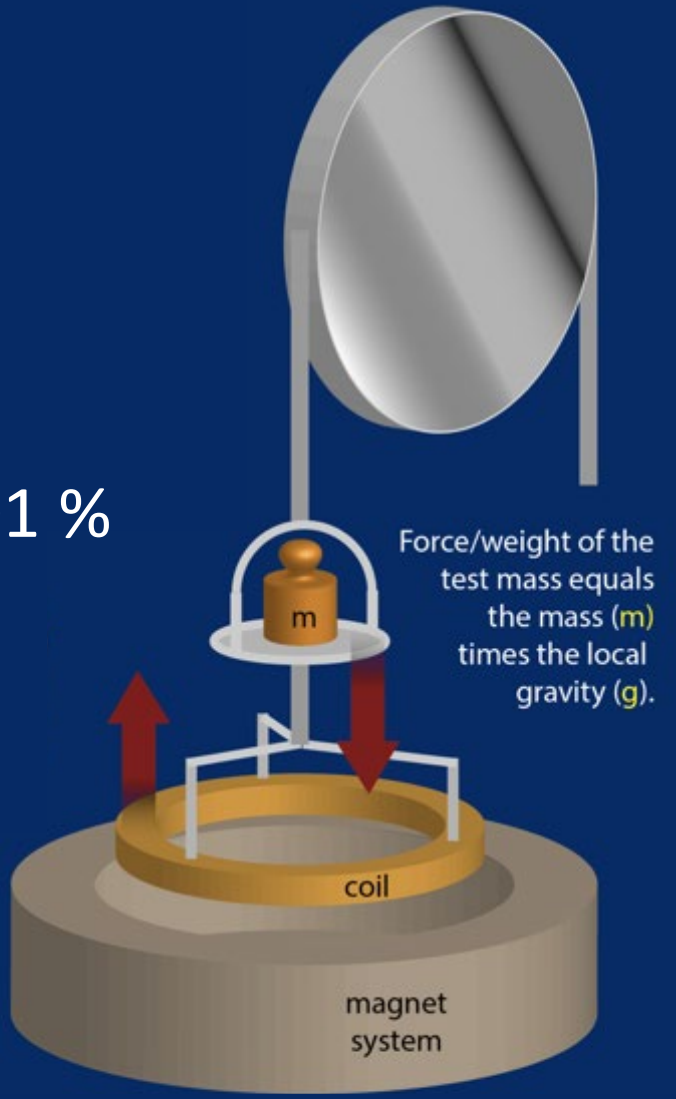
Kibble Balance ca. 2019

Best in the world uncertainty
0.01 % at 100 mg

Force = Power/c

Implies 100 kW can be measured at 0.01 %



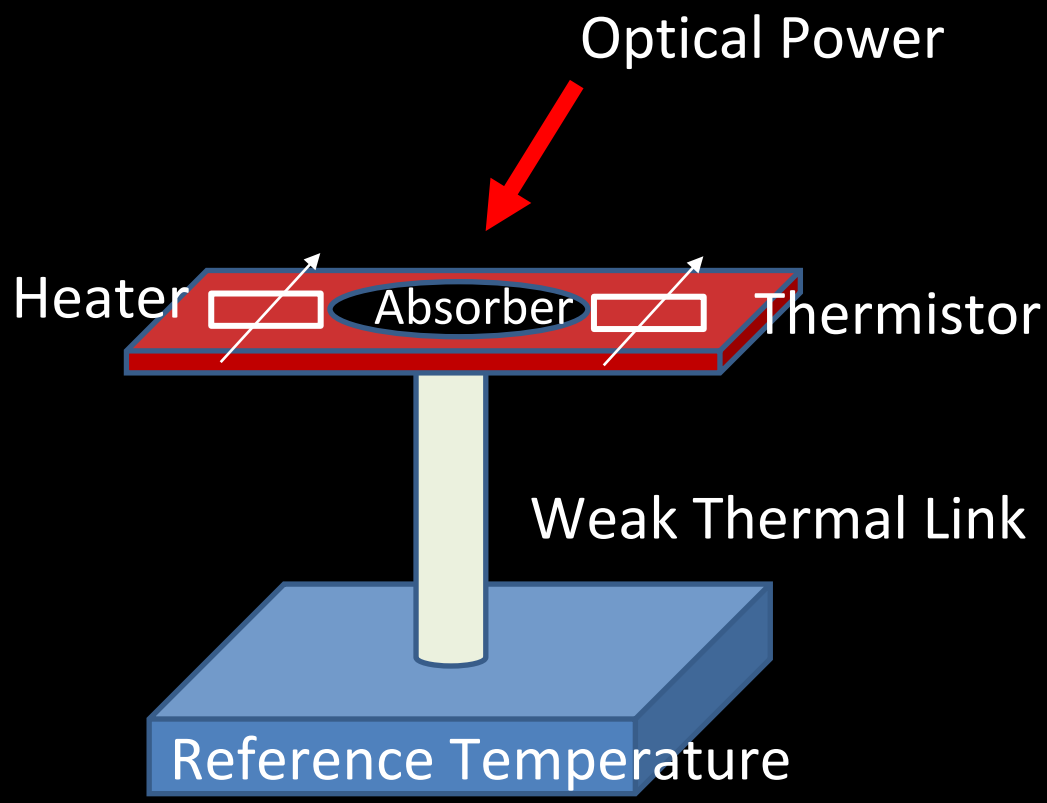


www.nist.gov

Simonds, et al., "Direct Realization of the Optical Watt from Planck's Constant," Metrologia, in press.

Optical Power

Present Primary Standardization



”Electrical Substitution”

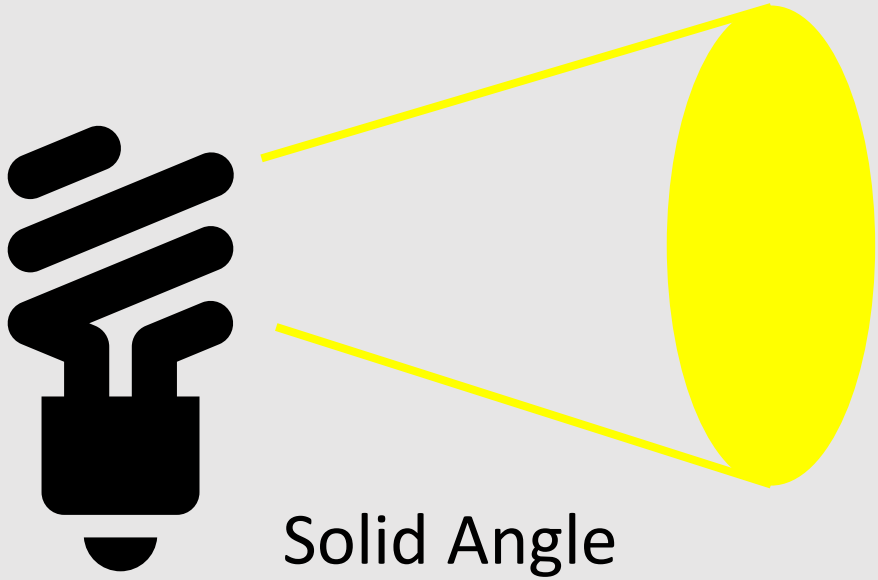
Best in the world
uncertainty < 0.01 %

Optical Power Traceable to the SI by Electrical Measurements
resistance, current, voltage

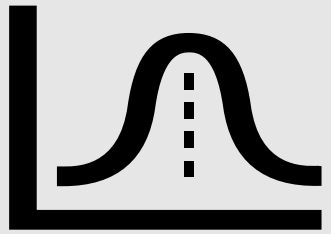
Counting

Light is Quantized

Optical Power



Solid Angle



λ = 555 nm

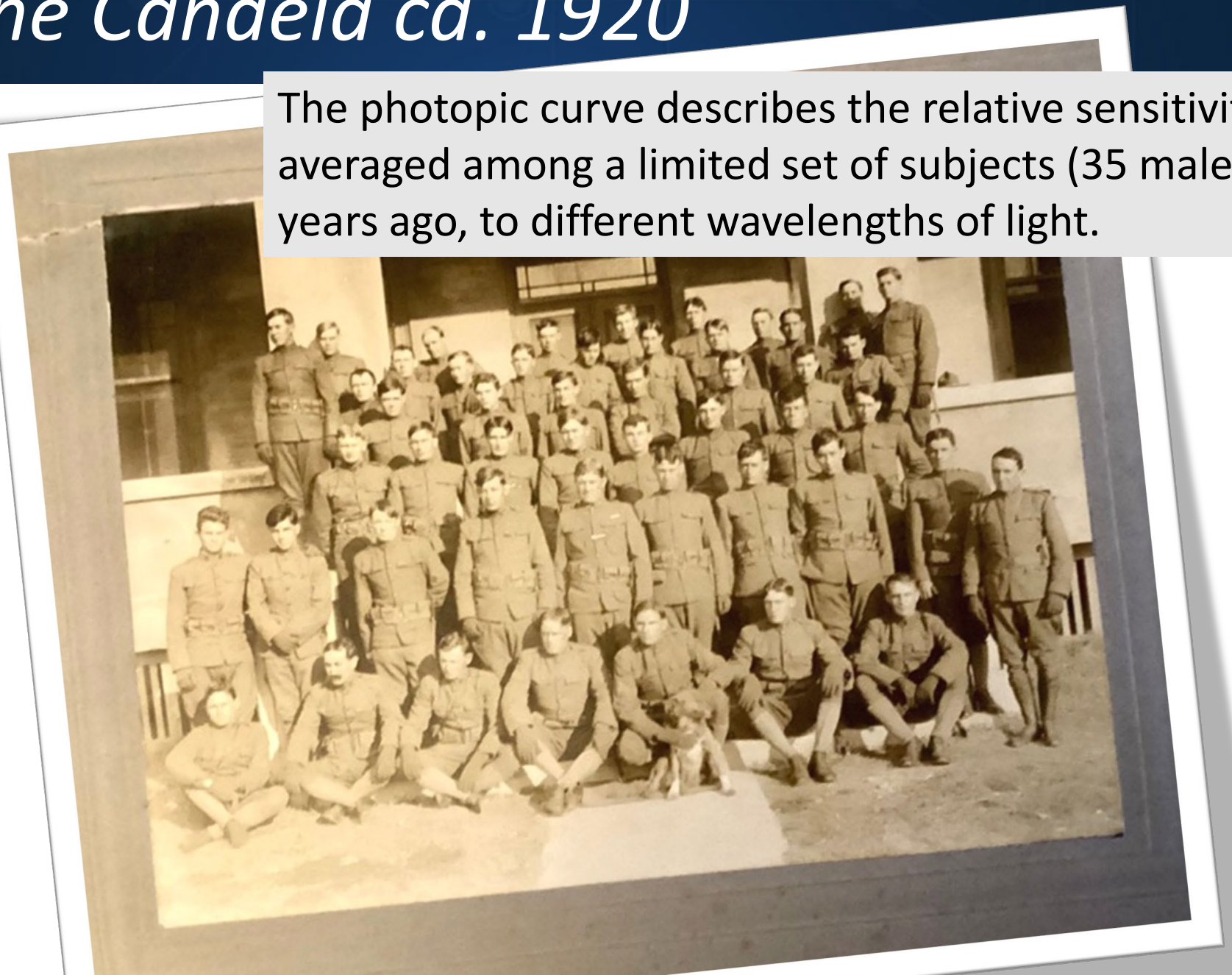
$k_{cd} = 683$

- Luminous intensity is **wavelength-weighted** optical power in a particular direction per solid angle.

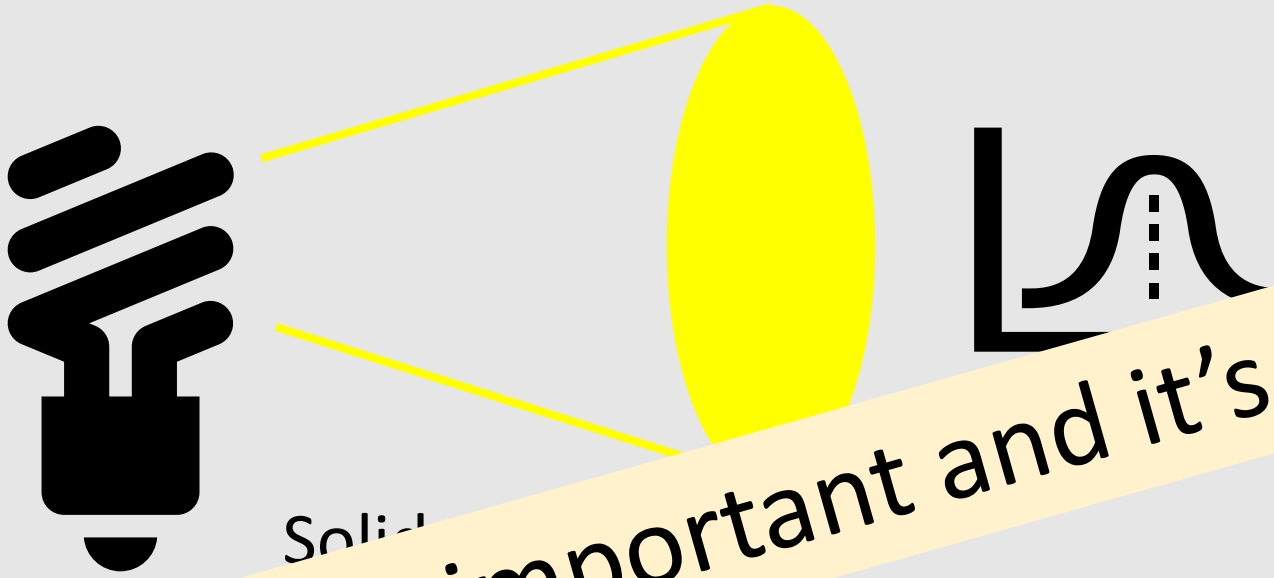
- The wavelength-weighting is based on CIE's luminosity function, but it is specified at a center wavelength (555 nm)

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.



2023: LED LIGHTING IS $80B INDUSTRY



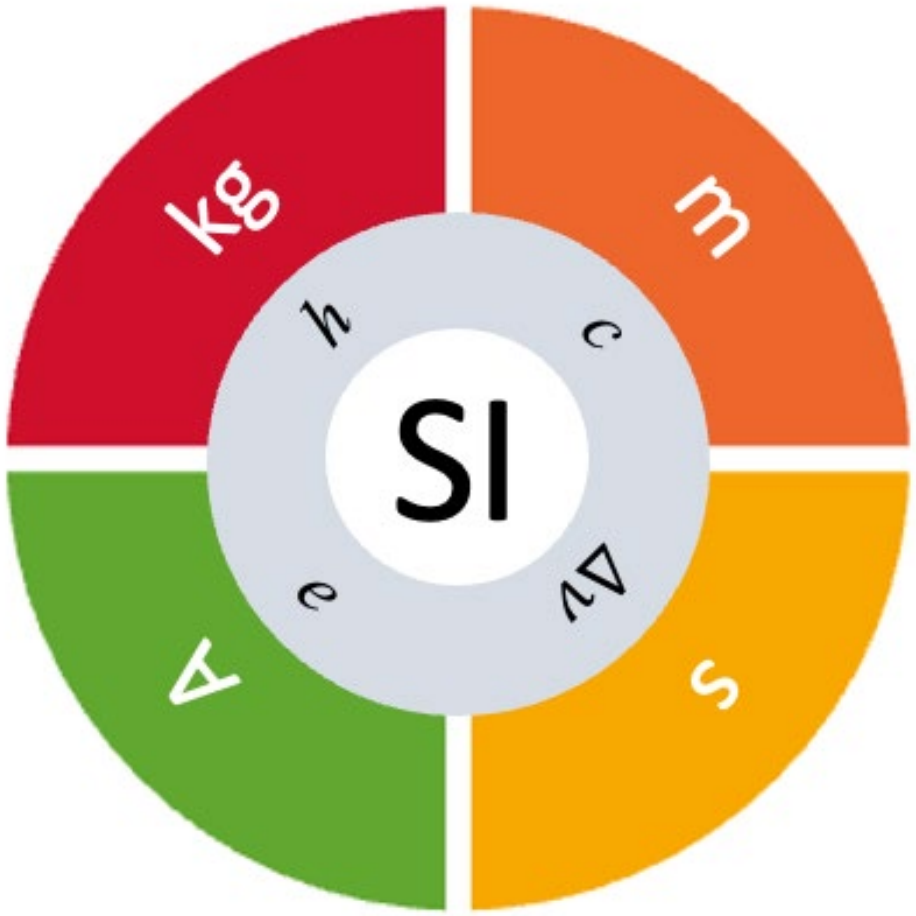
The candela is important and it's not going away!

- Solid ...ntensity 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)

SI Brochure

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

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



What if?

Tour de France ca. 1920

Tour de France ca. 1950


Tour de France ca. 2020
LOOK
795 BLADE RS
CORIMA
CORIMA


Physics
Engineering
Chemistry
Optimized (“humans”)
Convenient
10
LOUISBOBET


selleprima
SPINERGY
STEADY ROLLIN'

What is optimal?

Guiding Principles: A Design Challenge

Accessible:

Clear: Units and Constants are Causal (chicken v. egg).

Fair:

Reliability: The uncertainty in SI base units should be as small as possible.

Practical: “realizable” useful.

Stable: All times and places.

Base Units Q = {Q}[Q]

A =

Defining Constant	Dimensionality			
	kg	m	s	A
$\Delta\nu_{Cs}$	0	0	-1	0
c	0	1	-1	0
h	1	2	-1	0
e	0	0	1	1

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

*Davis R 2023 IEEE Instrum. Meas. Mag. 26 5–11

Base Units Q = {Q}[Q]

A^{-1} =

Unit	Dimensionality			
	$\Delta\nu_{Cs}$	c	h	e
kg	1	-2	1	0
m	-1	1	0	0
s	-1	0	0	0
A	1	0	1	1

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

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Base Units Q = {Q}[Q]

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Defining Constant	Dimensionality			
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A^{-1} =

Unit	Dimensionality			
	$\Delta\nu_{Cs}$	c	h	e
kg	1	-2	1	0
m	-1	1	0	0
s	-1	0	0	0
A	1	0	1	1

The system is coherent

- See Richard Davis*

This form is non-degenerate

- non-zero determinate
- invertible

Can be used to define everything else

*Davis R 2023 IEEE Instrum. Meas. Mag. 26 5–11

Base Units

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

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

What do we want! When do we want it!

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!)*

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.  *Optimize the SI wheel: it's not just physics, engineering, chemistry, industry, convenience.*

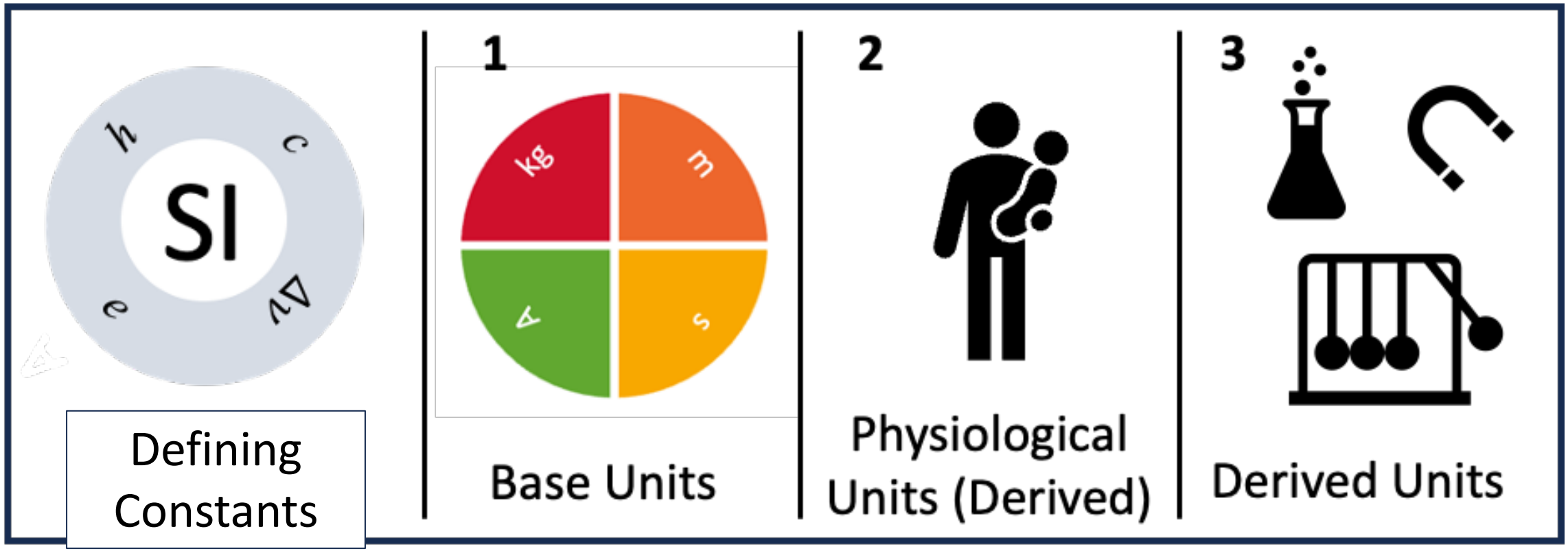
2. *"The distinction between the [4] base and derived units **is** fundamental."*

   - *or: get rid of modifiers (just constants and units)*

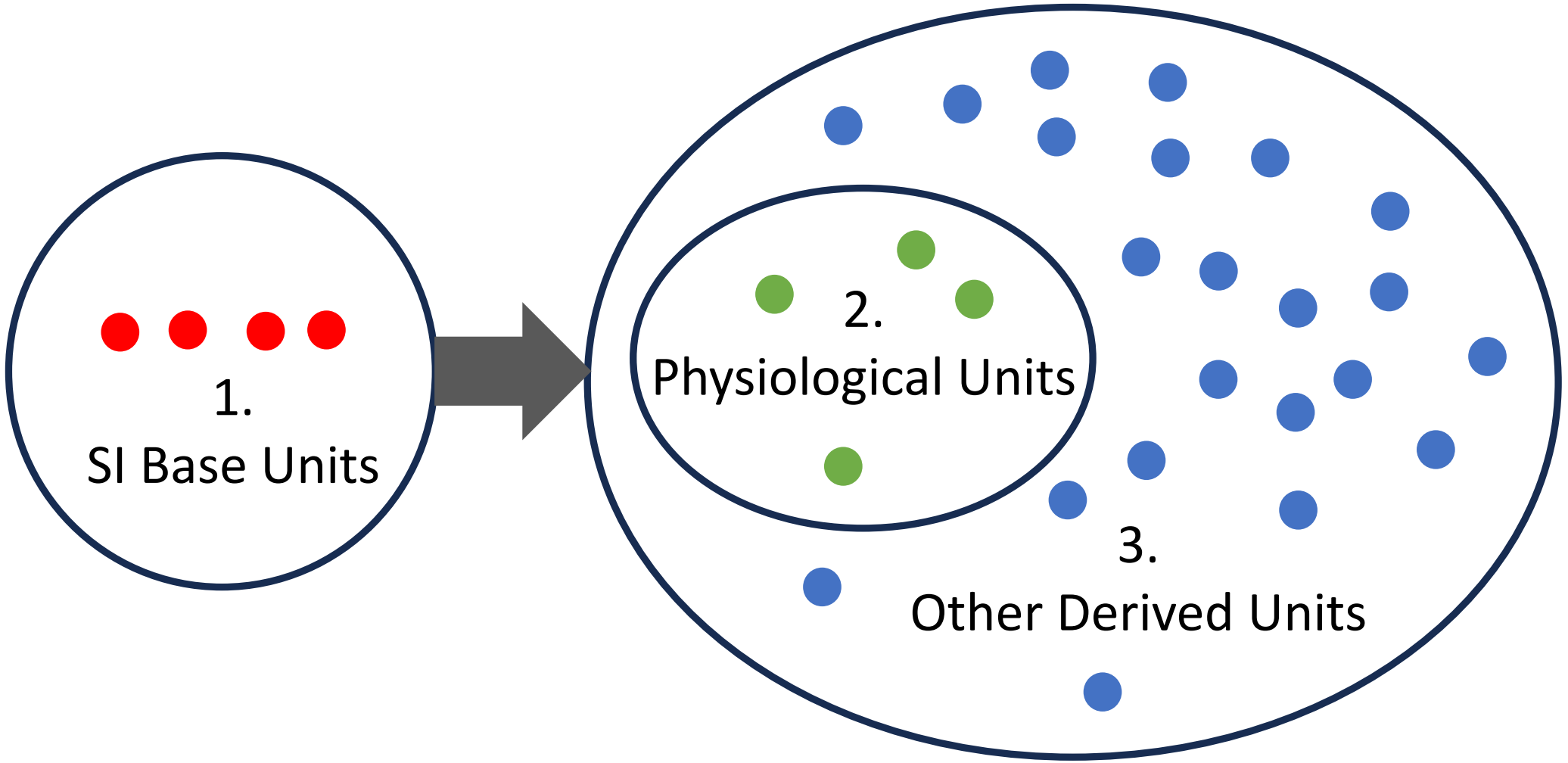
3. *CCPR SP resolution to have a conversation?*

Proposal 1

Lehman, et al., Metrologia 61 (2024) 033001



SI



Basic Units

Category 1 – Four basic physics units: time (s), length (m), mass (kg), and current (A). These are exclusively the defining constants with corresponding base units.

Physiological Units

Category 2 – *Non-physics* units that are useful in quantifying human perception, and for practical and/or historic reasons there has been a compelling reason to standardize them: e.g., candela, lumen, lux, and sievert.

[see: Nelson and Ruby, 1983 **DOI** 10.1088/0026-1394/30/2/001]

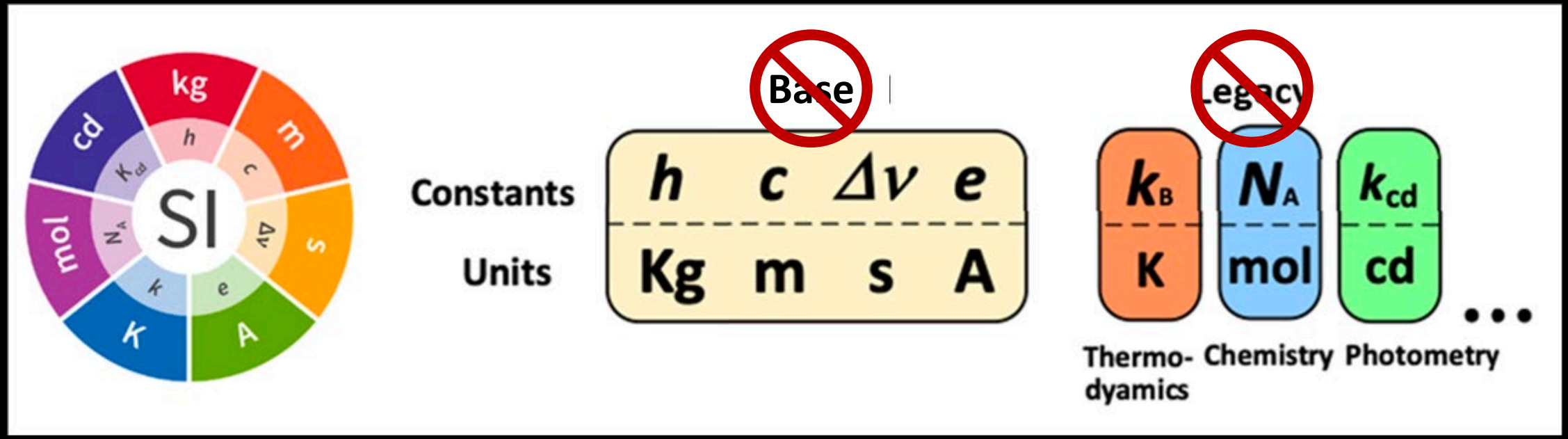
Everything Else

Category 3 – Additional *physics* units that provide no additional scientific information, but for practical and/or historic reasons, it is worthwhile to standardize them. (The two current examples being the mole and the kelvin.)

Proposal 2

	Base				Legacy			
Constants	h	c	$\Delta\nu$	e	k_B	N_A	k_{cd}	...
Units	Kg	m	s	A	K	mol	cd	
					Thermo-dyamics	Chemistry	Photometry	

Or just units and constants!



SI

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Reliability
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