Metrology and standardization

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Geneva, 14 October 2020

My profile

M.Sc. in physics; Ph.D. in measurement science.
Full professor of measurement science at Università Cattaneo – LIUC, Castellanza (VA), Italy: at LIUC teacher of courses on measurement science, statistical data analysis, system theory.

Currently chair of TC 1 (Terminology) and secretary of TC 25 (Quantities and Units) of the International Electrotechnical Commission (IEC), and an IEC expert in the WG 2 (VIM) of the Joint Committee for Guides in Metrology (JCGM). He has been the chairman of the TC 7 (Measurement Science) of the International Measurement Confederation (IMEKO).

Author or coauthor of several scientific papers published in international journals and international conference proceedings.

Some of my recent publications

LM, C.Narduzzi, G.Nordin, S.Trapmann, **Foundations of uncertainty in evaluation of nominal properties**, Measurement, 2020

LM, J.Goodwin, E.Jacobson, L.Pendrill, **The definitions of the base units in the revised SI: a terminological analysis**, *Measurement*, 2020

A.Giordani, LM, **A structural model of direct measurement**, *Measurement*, 2019

A.Maul, LM, M.Wilson, **Intersubjectivity of measurement across the sciences**, *Measurement*, 2019

LM, C.D.Ehrlich, L.R.Pendrill, **Measurement units as quantities of objects or values of quantities: a discussion**, *Metrologia*, 2018

A.Maul, LM, D.Torres Irribarra, M.Wilson, **The quality of measurement results in terms of the structural features of the measurement process**, *Measurement*, 2018

LM, P.Carbone, A.Giordani, D.Petri, **A structural interpretation of measurement and some related epistemological issues**, *Studies in History and Philosophy of Science*, 2017

LM, **Toward a harmonized treatment of nominal properties in metrology**, *Metrologia*, 2017

LM, D.Petri, **The metrological culture in the context of Big Data: Managing data-driven decision confidence**, *IEEE Instrumentation and Measurement Magazine*, 2017

LM, P.Blattner, F.Pavese, **Improving the understandability of the next edition of the International System of Units (SI) by focusing on its conceptual structure**, *Measurement*, 2017

LM, A.Maul, D.Torres Irribarra, M.Wilson, **Quantities, quantification, and the necessary and sufficient conditions for measurement**, *Measurement*, 2017

D.Petri, LM, P.Carbone, **A structured methodology for measurement development**, *IEEE Trans. Instr. Meas.*, 2015

A.Mencattini, LM, **A conceptual framework for concept definition in measurement: the case of 'sensitivity'**, *Measurement*, 2015

LM, **Evolution of 30 years of the International Vocabulary of Metrology (VIM)**, *Metrologia*, 2015

This lecture

1. Introduction: justification
2. Backgrounder: basic concepts and terms
3. Standardization of measurement
4. Standardization in measurement
5. In the last twenty years...

References [xyz] are listed in the last slide

1. **Introduction: justification**
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Importance of measurement: examples

- Measuring the value of natural gas must be uniform and reliable throughout Europe in order to protect consumers and fiscal revenue
- Fundamental research in the measurement of electrolytic conductivity has direct impact on the quality of life for dialysis patients
- The measurement of airborne nanoparticles in the environment and workplace may help improve air quality and health
- Precise fertiliser spreaders reduce environmental impact and improve agricultural economy
- An intelligent solution for heat meters could reduce costs for the hundred million people in Northern Europe – and other cold parts of the world
- Are shrimps safe to eat? Understanding the measurements is important
- Measurements have a crucial role in cancer treatment
- Improved monitoring of the heat treatment of jet engine components could lead to reduced aircraft emissions

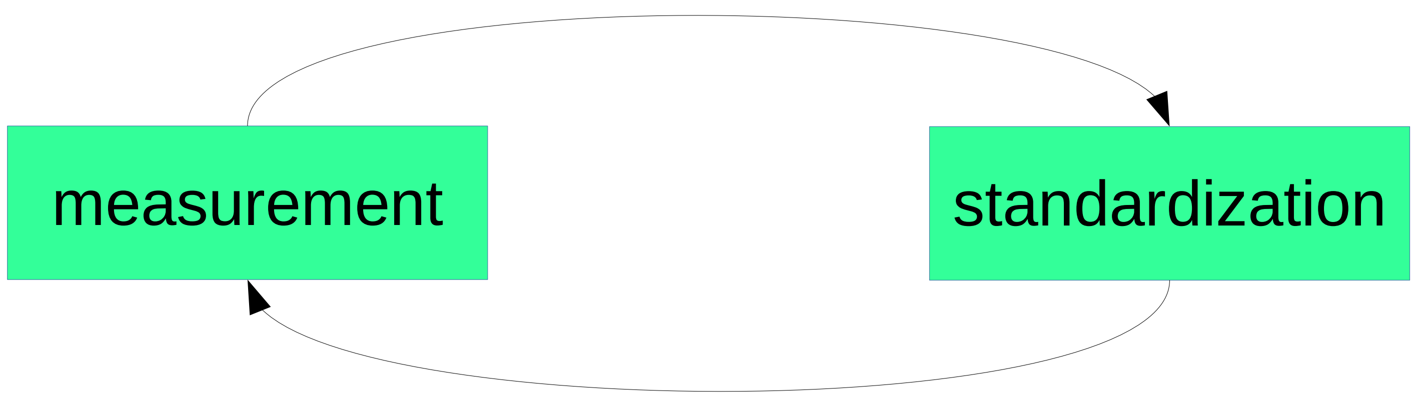
[MIS]

Metrology and standardization

What measurement can offer to standardization is quite clear

Less obvious is what measurement requires from standardization, and what should be standardized in measurement and why

Some analysis of what is measurement (and what is not) is appropriate, also to identify and remove some stereotypes



Measurement enables just society

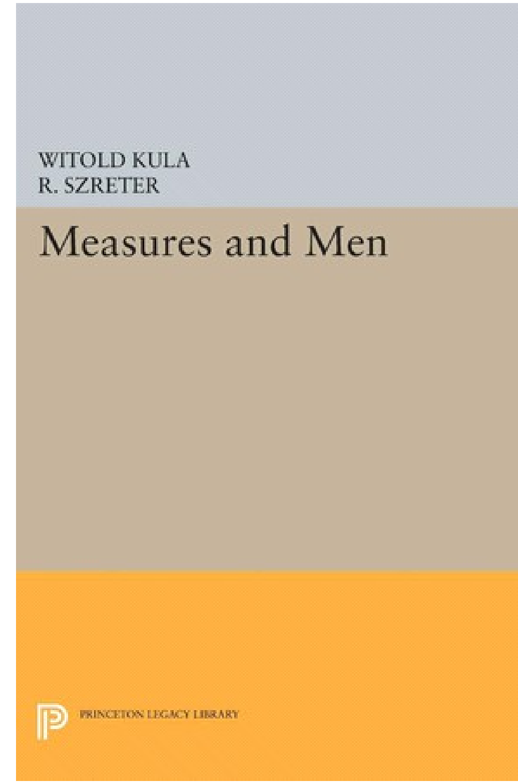
https://en.wikipedia.org/wiki/Lady_Justice

That a given object has a given weight **is a fact** independent of economical, political, religious, … positions

No fake news / alternative facts / post-truth in measurement...

Measurement enables just society?

Measures and Men (1986, 2014)
“considers times and societies
in which weighing and measuring were
weapons in class struggles”



in the years following the first period
of the French revolution, many asked

“what is the use to us of the abolition of the feudal system, if the *seigneurs* remain at liberty arbitrarily to increase or decrease their measures?”

No fake news in measurement: really?
How is this special feature justified?

How can measurement have this role? What is measurement?

Characterizing measurement

1. measurement is a **<u>source of public trust</u>**:

and this is NOT because
we know ***that*** we can rely on the information it produces,
but because
we know ***how much*** we can rely on it

(trustworthiness / public trust is also a reason of standardization, isn't it?)

2. measurement is the scientific and technical tool
that we have been developing and exploiting since millennia
to produce **<u>object-related and subject-independent information</u>**
("objective" and "intersubjective" for short)

(objectivity and intersubjectivity are also reasons of standardization, aren't they?)

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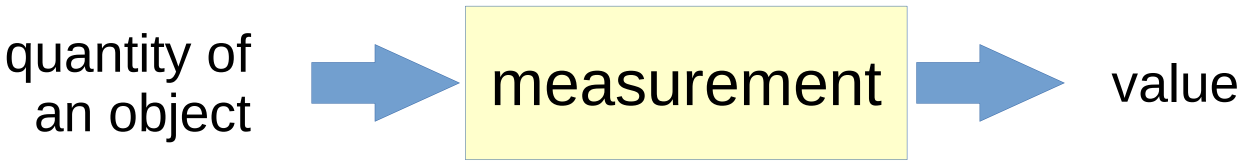
Measurement as a black box

Measurement is about **quantities** of **objects**,
and aims at producing information on them as **values**



Basic concepts and terms

Hence the entities under consideration are:

- a **measurer**, interested in acquiring information on
- a **quantity** (e.g., weight *W*)
- of an **object** (e.g., the object *a*)
- by means of a **measuring instrument** (e.g., a weighing scale)
- used to perform a **measurement** (which is a process)
- which in the simplest case produces a **value** (e.g., 0.123 kg)
- so that the **measurement result** about the **measurand** $W(a)$ is

  $W(a) = 0.123$ kg

  i.e., the weight of the object is 0.123 kg

The fundamental requirement

Let us suppose that someone in Geneva weighed an object *a*
and obtained $W(a) = 0.123$ kg,
and that someone else in Milano weighed an object *b*
and obtained $W(b) = 0.123$ kg

If we rely on this information, we agree that $W(a) = W(b)$,
and therefore *a* and *b* have the same weight,
even though we never compared *a* and *b* directly

if *same value* then *same weight*:

how can we guarantee this?

Three conditions

From the measurement results $W(a) = 0.123$ kg and $W(b) = 0.123$ kg we can reliably infer $W(a) = W(b)$ if

C1. the kilogram is the same weight in Geneva and in Milano

C2. the weighing scales used in Geneva and in Milano produce the same value, 1 kg, when measuring the weight of an object of one kilogram

C3. the weighing scales used in Geneva and in Milano behave in the same way when measuring the weight of objects of less or more than one kilogram

C1 and C2 are about standardization: when they are fulfilled, C3 is only about the technical quality of the instruments

Let us focus on C1 and C2

Unit definition and realization

The kilogram is a weight defined in some way,
but we cannot make our instruments interact with a definition!

We need objects weighing one kilogram,
which then materialize the unit by realizing its definition

An object which realizes the definition of a unit is called
a **measurement standard**

“standard” has (at least) two meanings:
→ a document such that...
→ an entity that realizes a reference quantity

Let’s do it by ourselves...

… by defining the geneva, symbol g, as a unit of weight

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Standardization of measurement: Condition 1

C1. The geneva must be the same weight everywhere

Intersubjectivity

The fundamental claim of measurement is that a sentence such as

$W(a) = 2$ g

must have **the same meaning everytime and everywhere**,
so that **its interpretation is subject-independent**
(and then socially free from arbitrariness)

(*2 genevas, today and tomorrow, here and in Milano, must be the same weight*)

This implies that the unit g must be:

- **stable** ("everytime" constraint)
- **accessible** ("everywhere" constraint)

A strategic solution to this problem requires scientific, technological, organizational, and political means:

a metrological system

stability ("everytime")

Unit definition

A significant example, the metre:

option 1. the distance between the axes of two lines marked on a given bar in given conditions

option 2. a given fraction of the length of a given earth meridian from pole to the equator

option 3. the length of the path traveled by light in vacuum during a given time interval

option 1. low stability no theory	option 2. fair stability almost no theory	option 3. maximum stability theory-laden

Extreme cases

In the International System of Units (Système International d’Unités, SI), until May 2019:

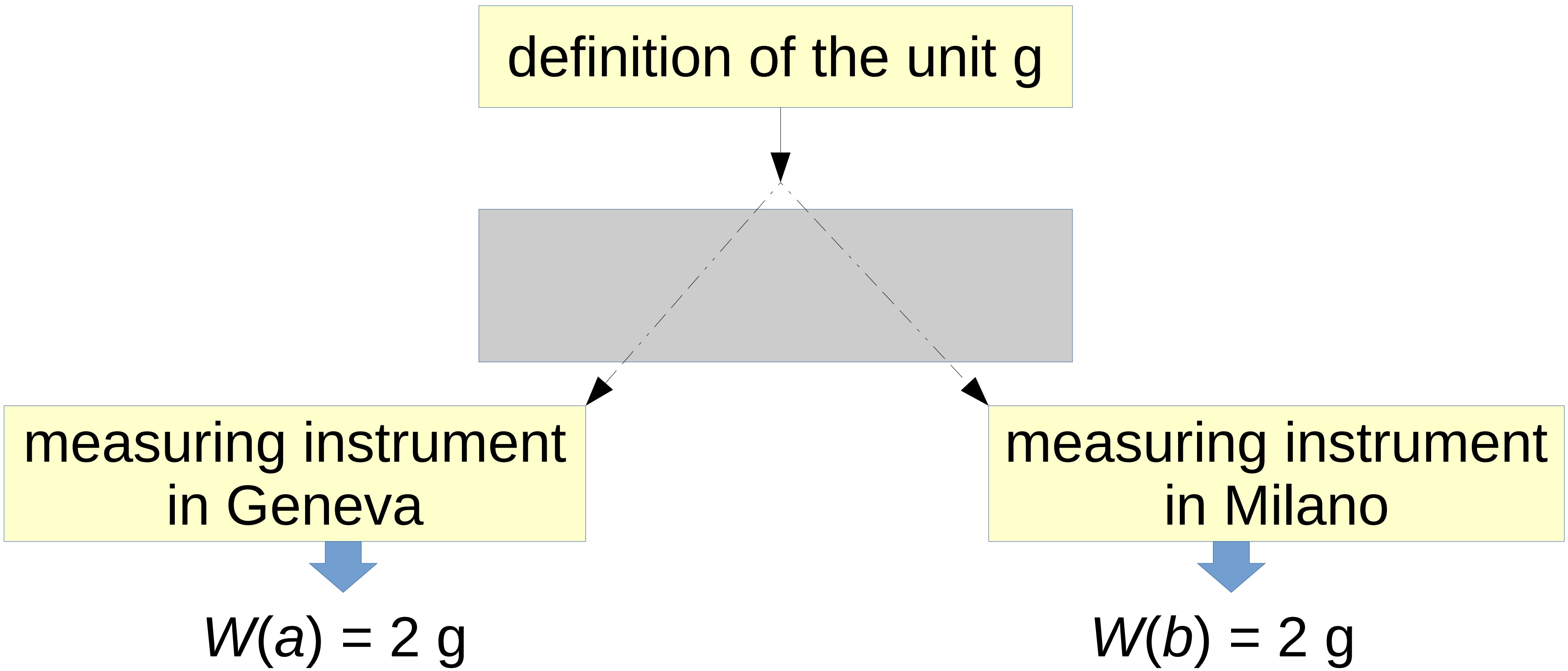
“The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.”
(*a definition referring to a concrete, individual object*)

“The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per metre of length.”
(*a definition referring to an abstract, ideal phenomenon*)

[SIB]

accessibility (“everywhere”)

Metrological traceability



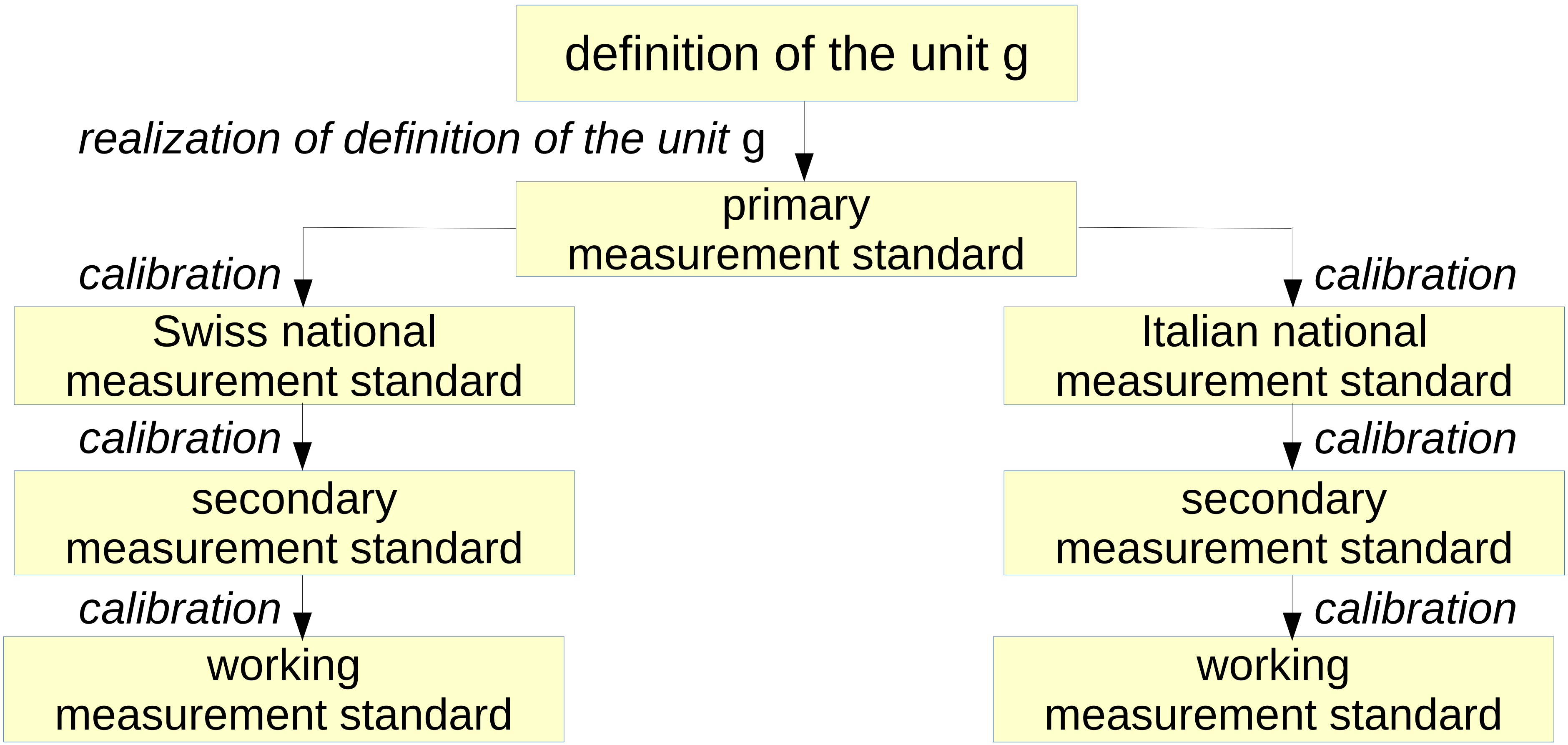
ONLY IF the gray box reliably transfers g,
THEN we can safely infer that $W(a) = W(b)$

(i.e., that measurement results convey intersubjective information)

<u>metrological traceability</u>: “property of a measurement result whereby the result can be related to a reference through a documented unbroken chain...”

[VIM]

Metrological traceability chain



metrological traceability chain: “sequence of measurement standards and calibrations that is used to relate a measurement result to a reference”

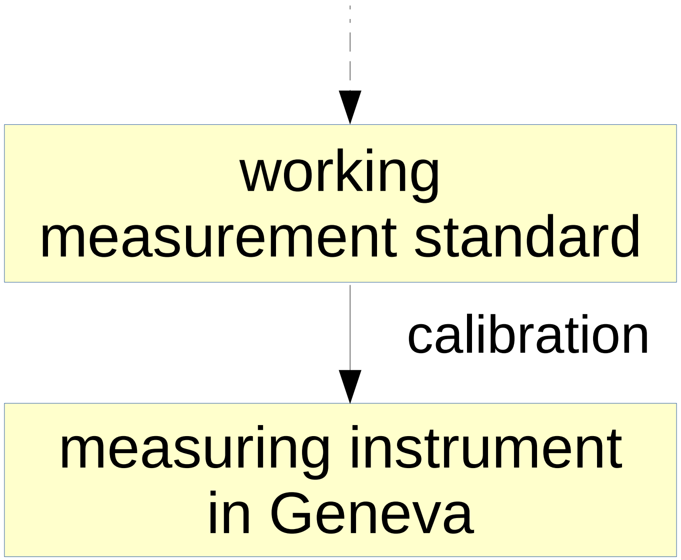
[VIM]

Standardization of measurement: Condition 2

C2. Instruments produce everywhere the same value, 1 g, when measuring the weight of an object of one geneva accessibility (“everywhere”)

Metrological traceability chain

Completing the chain, then...

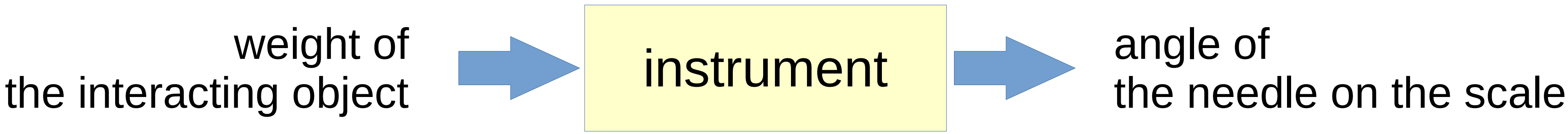


<u>metrological traceability chain</u>: “sequence of measurement standards and calibrations that is used to relate a measurement result to a reference”

[VIM]

Calibrating a measuring instrument

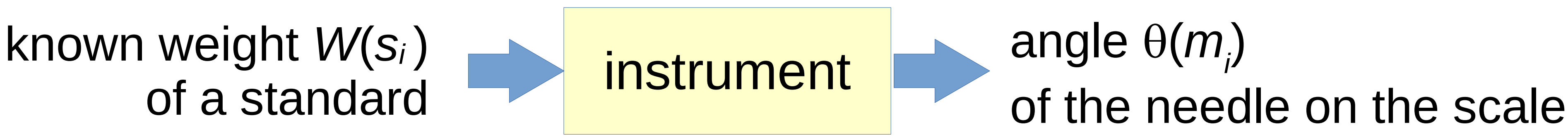
Let us consider the simple case of a weighing scale with analog reading, which physically operates as a **transducer**, that maps weights (input) to angles (output):



What we can “read” is the angle:
how, from this reading, can we infer the weight?

Calibrating a measuring instrument

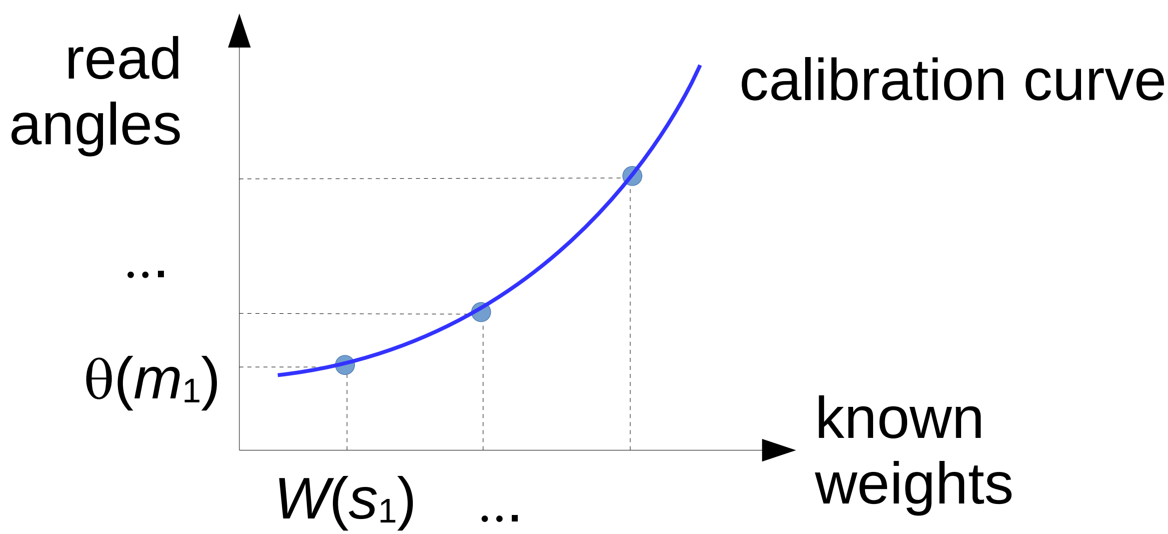
Let us assume that we can make the weighing scale interact with weight standards, so that:



For each standard we obtain a pair

<known weight $W(s_i)$, read angle $\theta(m_i)$>

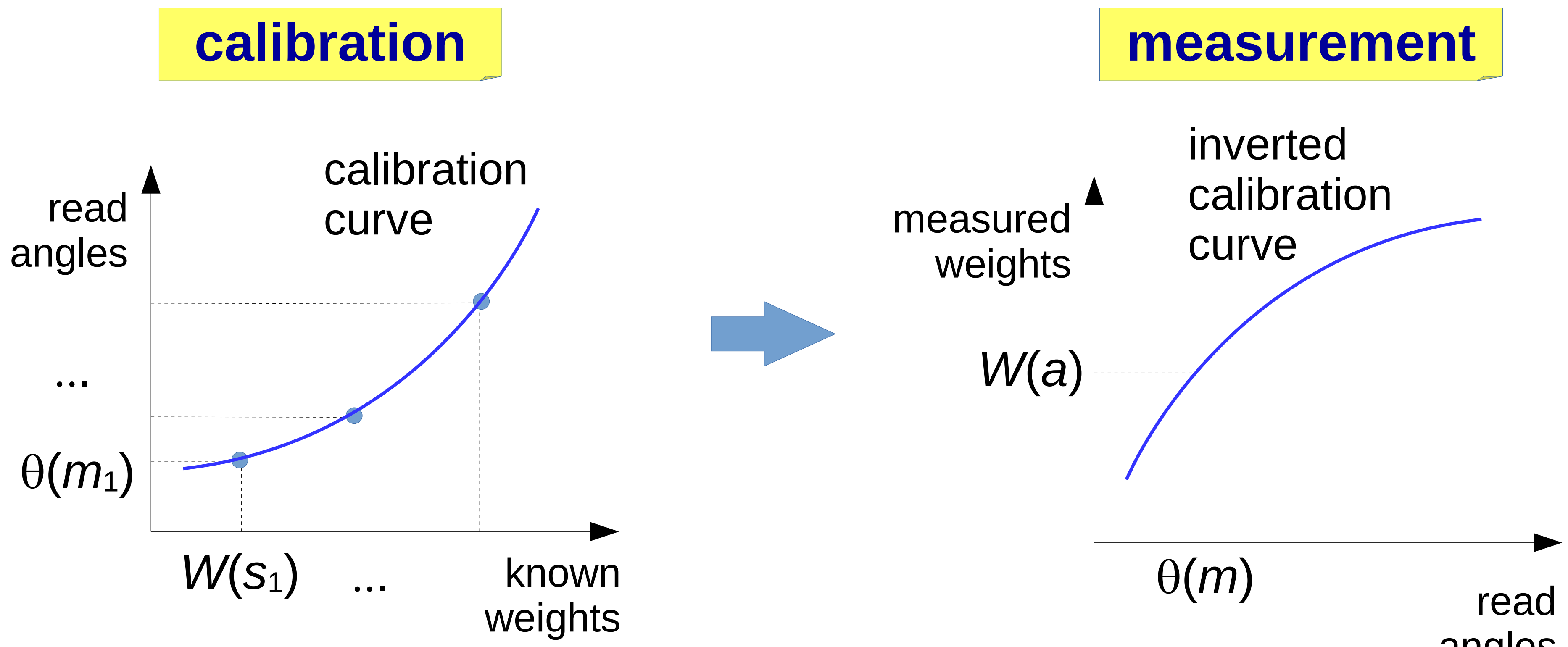
In a chart:



accessibility ("everywhere")

From calibration to measurement

Let us assume that the calibration curve can be inverted
Then:



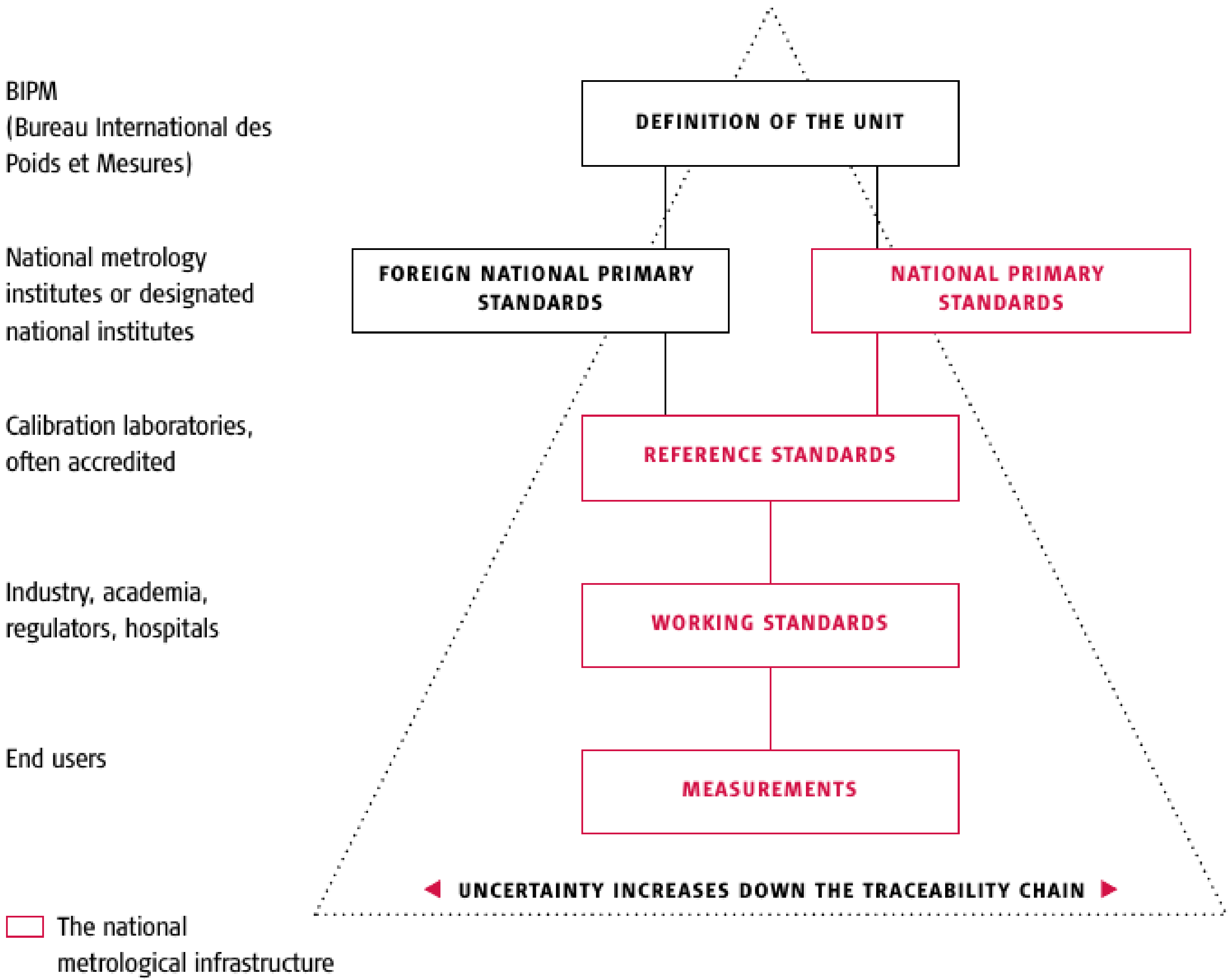
A fundamental concept: measurement uncertainty

Interestingly, the characterization so far applies identically to common life measurements (say, weighing at the supermarket) and to super-sophisticated ones, even though the quality of such processes, and therefore of their results, is dramatically different

We assess and report the quality of measurement results in terms of **measurement uncertainty**

Both calibration and measurement results are generally affected by some uncertainty

The metrological system



[MIS]

Measurement uncertainty

<u>measurement uncertainty</u>:
"non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used"

[VIM]

The example of a measurement result:

$W(a) = 0.123(2)$ g

meaning that we are uncertain of the last decimal digit:

the value might be in the interval 0.123 g ± 0.002 g

(*simplified version: a more correct version should be probabilistic*)

Measurement uncertainty is inversely related to the quantity of information claimed to be conveyed by a measurement result

The critical consequence

A measurement result stated without uncertainty implicitly claims to convey an infinite (?!) quantity of information

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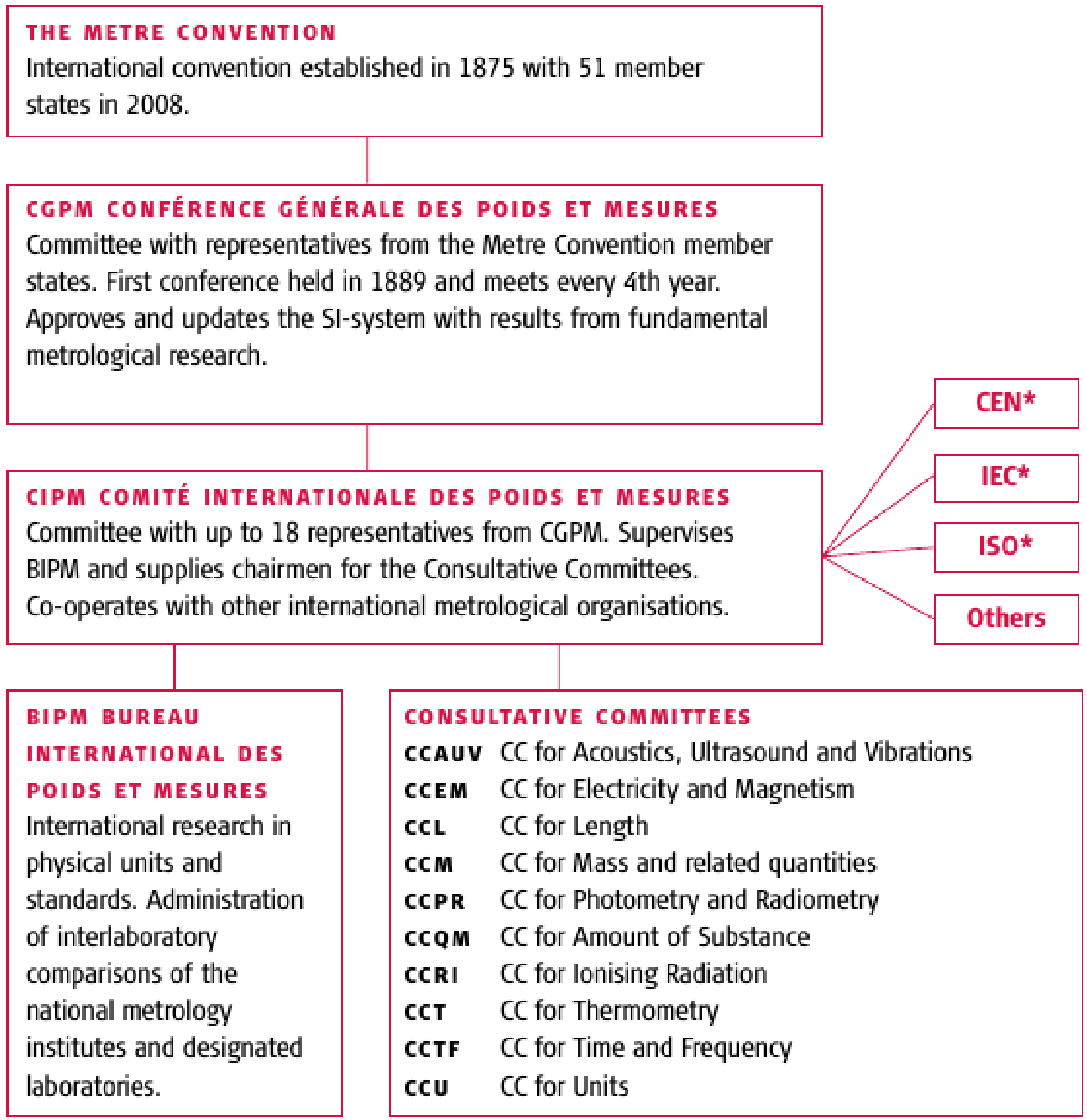
Standardization in measurement

Metrological systems are then the main target
of standardization in measurement:

- **units and their dissemination**
- **methods for uncertainty evaluation and reporting**
- **terminology**

The (political and) scientific side



[MIS]

The (political and) legal side

[https://www.oiml.org]

For Your Information...

29.3.2014 EN Official Journal of the European Union L 96/149

DIRECTIVE 2014/32/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 26 February 2014

on the harmonisation of the laws of the Member States relating to the making available on the market of measuring instruments (recast)

an update of

DIRECTIVE 2004/22/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 31 March 2004

on measuring instruments

[MID]

Measurement is everywhere

... and several institutions are interested in standardizing it

“In 1997 the Joint Committee for Guides in Metrology (JCGM) was formed ...

- to develop and maintain, at the international level, guidance documents addressing the general metrological needs of science and technology, and to consider arrangements for their dissemination
- to promote worldwide adoption and implementation of the results of its work;
- to provide advice, when requested, on questions related to the implementation of its guidance documents”

JCGM

The current membership of the Joint Committee:

- the two inter-governmental organizations concerned with metrology:
    1. the Bureau International des Poids et Mesures (**BIPM**)
    2. the Organisation Internationale de Métrologie Légale (**OIML**)
- the two principal international standardization organizations:
    3. the International Organization for Standardization (**ISO**)
    4. the International Electrotechnical Commission (**IEC**)
- three international unions:
    5. the International Union of Pure and Applied Chemistry (**IUPAC**)
    6. the International Union of Pure and Applied Physics (**IUPAP**)
    7. the International Federation of Clinical Chemistry and Laboratory Medicine (**IFCC**)
- one international accreditation organization
    8. the International Laboratory Accreditation Cooperation (**ILAC**)

Decision making principle

Decisions of the Joint Committee shall be by **consensus**, bearing in mind the following definition:

consensus: General agreement characterized by the absence of sustained opposition to substantial issues by any important part of the concerned interests and by a process that involves seeking to take into account the views of all parties concerned and to reconcile any conflicting arguments.
Note Consensus need not imply unanimity

[ISO/IEC Guide 2:2004, Standardization and related activities – General vocabulary, ISO, IEC, 2004]

JCGM guidance docs

the "VIM"

the "GUM"

http://www.bipm.org/en/publications/guides/ vim.html
gum.html

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5. **In the last twenty years:**
    - MRA
    - SI reform

Traceability again

If the unit u is defined through its realization ("case 1", e.g., metre as length of an object), the "owner" of the primary measurement standard is the top layer of the metrological system:
→ this is the role traditionally played by the BIPM

But if the unit u is defined in reference to a universal phenomenon ("case 3", e.g., metre from speed of light), there can be multiple ways to realize it, and none of them is in principle privileged
→ what can be the role of BIPM in this case?
→ towards a "Do It Yourself" metrological system?

Mutual Recognition Arrangement

For each quantity:

1. two or more NMIs, independently of one another, realize the unit
2. then compare their measurement standards
3. and together establish the value of the quantity of each standard

This is the core content of the Mutual Recognition Arrangement (MRA), signed in 1999, which creates a **“federated” metrological system**

BIPM has the role of coordinating steps 2 and 3, and of publishing their results in the Key Comparison Database

[http://kcdb.bipm.org]

Until May 2019...

All three cases of unit definition

(1. the distance between the axes of two lines marked on a given bar in given conditions
2. a given fraction of the length of a given earth meridian from pole to the equator
3. the length of the path traveled by light in vacuum during a given time interval)

share the same pattern:

1. Physics provides a **system of quantities**: “set of quantities together with a set of noncontradictory equations relating those quantities”
2. on this basis, a set of independent **base quantities** is decided (in the **International System of Quantities**, ISQ: length, mass, time, electric current, thermodynamic temperature, amount of substance, luminous intensity), such that each non-base quantity is derived from base quantities through such equations
3. for each base quantity a **base unit** is defined; the same equations applied to such base units define derived units, thus obtaining a **system of units** (the ISQ is the basis of the **International System of Units**, SI, in which base units are metre, kilogram, second, etc)

... and today

From the same system of quantities (of course...) a set of universal constants (speed of light, charge of electron, etc) is identified and:

- **the value of each of such constants is assigned**
- **each unit is defined as the quantity that if assumed as unitary is compatible with the assigned values of the constants**

Consequences:

- all unit definitions have the same structure
- unit definitions derive from previous definitions (“the constant x has numerical value y in the given units”)
- this assumes “bootstrap” definitions: each unit is defined in reference to values of constants, and the numerical value of each constant is defined in reference to such units
- there is distinction between base quantities/units and derived quantities/units
- each unit can be realized in different ways

- the meaning of unit definitions is much harder to explain...

An example: the metre

Until May 2019:

“The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second”

Today:

“The metre, symbol m, is the SI unit of length. It is defined by taking the fixed numerical value of the speed of light in vacuum *c* to be 299 792 458 when expressed in the unit m s^{-1}, where the second is defined in terms of the caesium frequency $\Delta\nu_{Cs}$”

References

[GUM] **JCGM 100:2008, Evaluation of measurement data – Guide to the expression of uncertainty in measurement (GUM)**, Joint Committee for Guides in Metrology, 1993 upd 2008
http://www.bipm.org/en/publications/guides/gum.html

[MID] **Directive 2014/32/EU of the European Parliament and of the Council of 26 February 2014 on the harmonisation of the laws of the Member States relating to the making available on the market of measuring instruments**
http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014L0032

[MIS] **Metrology in short**, 3rd ed, Euramet, 2008
https://www.euramet.org/publications-media-centre/documents/metrology-in-short

[SIB] **SI Brochure: The International System of Units (SI)**, 8th ed, BIPM, 2006 upd 2014
http://www.bipm.org/en/publications/si-brochure

[VIM] **JCGM 200:2012, International Vocabulary of Metrology – Basic and general concepts and associated terms (VIM)**, 3rd ed, Joint Committee for Guides in Metrology, 2008 upd 2012
http://www.bipm.org/en/publications/guides/vim.html

Thanks for your kind attention

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