Metrology and standardization

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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, 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, **Can formal methods provide (necessary and) sufficient conditions for measurement?**, *Measurement: Interdisciplinary Research and Perspectives*, 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

LM, D.Petri, **Measurement science: constructing bridges between reality and knowledge**, *IEEE Instrumentation and Measurement Magazine*, 2014

P.Micheli, LM, **The theory and practice of performance measurement**, *Management Accounting Research*, 2014

LM, M.Wilson, **An introduction to the Rasch measurement approach for metrologists**, *Measurement*, 2014

A.Frigerio, A.Giordani, LM, **On representing information: a characterization of the analog/digital distinction**, *Dialectica*, 2013

LM, **A quest for the definition of measurement**, *Measurement*, 2013

This lecture

1. Introduction: justification
2. Backgrounder: basic concepts
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

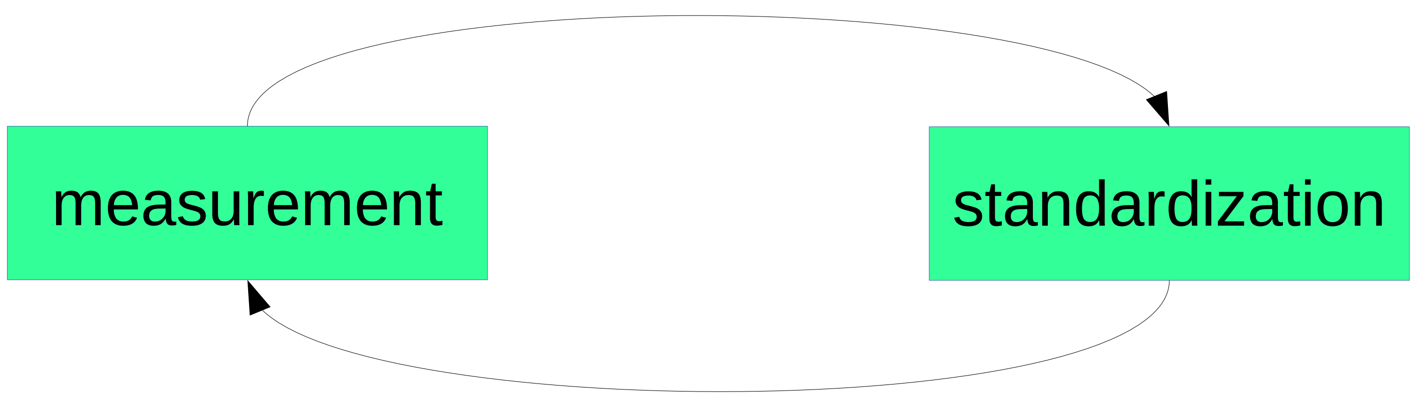
[MIS]

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

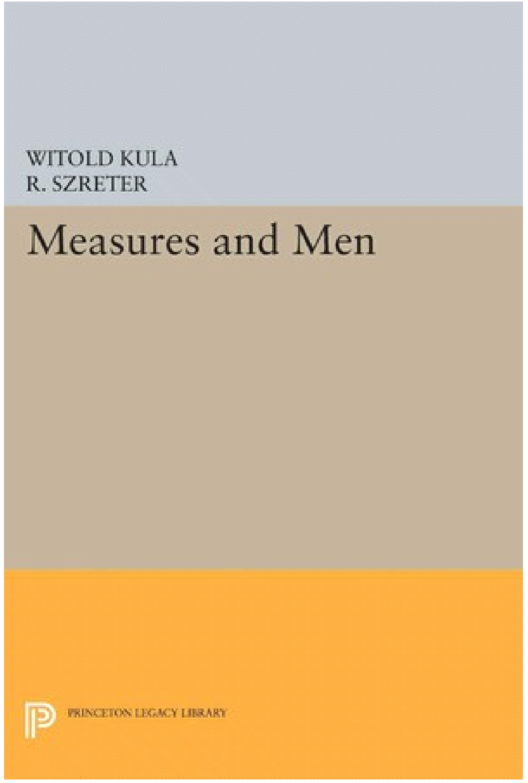
https://en.wikipedia.org/wiki/Lady_Justice

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?

Measurement vs (expert) opinion

It is NOT a matter of quality of the produced information:

the concept ‘bad measurement’ is not contradictory,
and bad measurements can produce information worse than the information produced by good opinions

what is the difference between measurement and opinion then?

(it is NOT that measurements produce ***quantitative*** information: also opinions can)
(it is NOT that measurements produce ***consistent*** information: also opinions can)

Characterizing measurement

(I am NOT aware of any established conceptual framework that provides an answer to this fundamental problem)

(I am going to present you my position on this subject)

Thesis 1

measurement is a **source of public trust**:

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?)

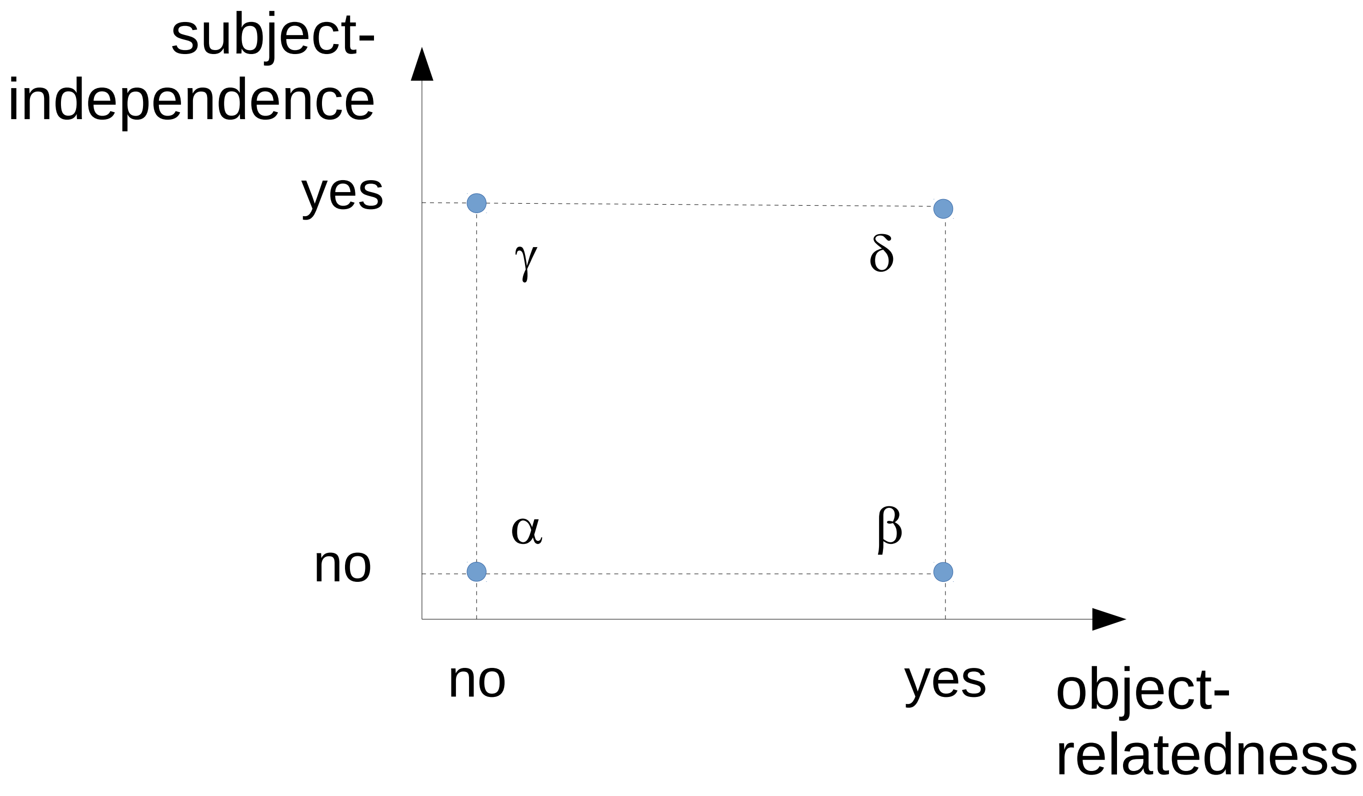
The basic features of measurement

Thesis 2

measurement is the scientific and technical tool
that we have been developing and exploiting since millennia
to produce information that is
object-related and **subject-independent**
(“objective” and “intersubjective” for short)

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

Object-relatedness and subject-independence



Can you describe examples of α, β, γ, δ ?

The basic features of measurement

how can measurement results be objective and intersubjective?

In this lecture we will mainly explore intersubjectivity in measurement, a topic explicitly related to standardization

(objectivity is about the quality of instrumentation)

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Quantities

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

Hence the entities under consideration are:

- an **object**, e.g., the object a
- a **general quantity**, e.g., weight W
- an **individual quantity**, e.g., the weight of the object a, $W(a)$
- a **value**, e.g., 2 kg

and a simple example of a **measurement result** is then:

$W(a) = 2$ kg

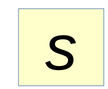
i.e., the weight of the object a is 2 kg

Measurement results

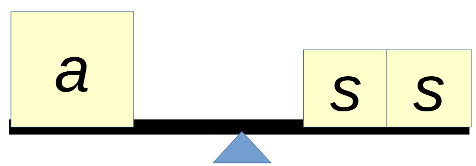
A simple example of a **measurement result** is $W(a) = 2$ kg

What does it mean?

1. We agreed to identify a given weight…
2. … for example as the weight of a given object *s*



3. We agreed to give that weight a name, e.g., “kilogram”
4. We compared the objects *a* and *s* by weight…
5. and discovered that



6. that is, $W(a) = 2\ W(s)$
7. But since $W(s) =$ kg…
8. … the measurement result is $W(a) = 2$ kg

Quantities and numbers

A relation such as:

$$W(a) = 2\text{ kg}$$

can be then interpreted as:

$$W(a)\ /\ \text{kg} = 2$$

This is at the basis of the traditional Euclidean standpoint:

quantities can be compared by ratio and a ratio of quantities is a number

"By Number we understand [...] the abstracted Ratio of any Quantity, to another Quantity of the same Kind, which we take for Unity."

[I.Newton, Universal arithmetick – A treatise of arithmetical composition and resolution, 1769]

Measurement and quantification

Of course, one can obtain a result such as:

$$W(a) = 2 \text{ kg}$$

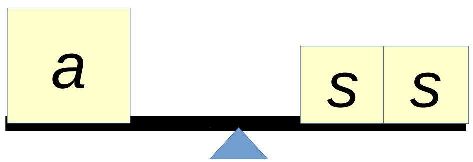
also through judgment by experience, guess, …

Numbers (with units) can be arbitrarily assigned: they are (maybe necessary but) surely not sufficient to guarantee the target of trustworthiness

(measurement ≠ quantification)

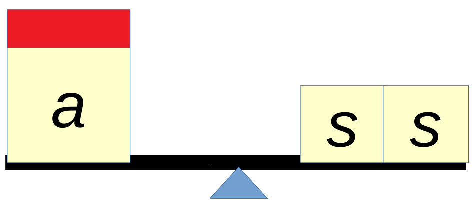
Trustworthiness of measurement

0



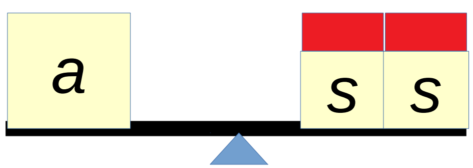
$W(a) = 2$ kg

1

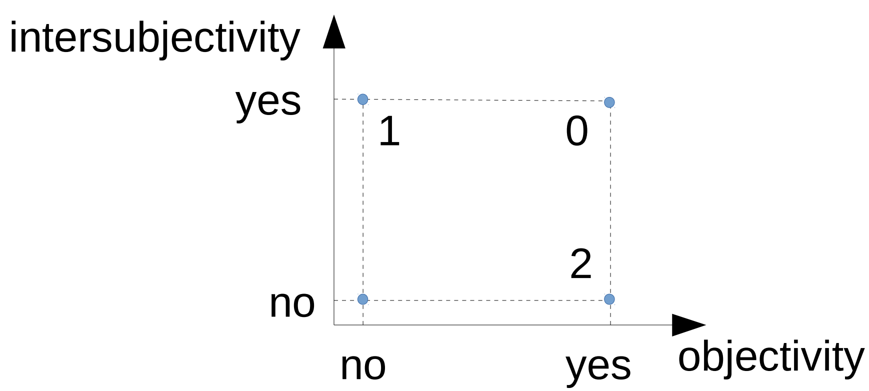


If we report it as $W(a) = 2$ kg
we have a problem of **objectivity**

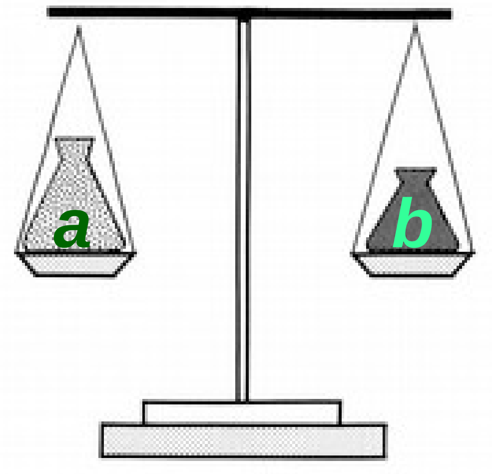
2



If we report it as $W(a) = 2$ kg
we have a problem of **intersubjectivity**



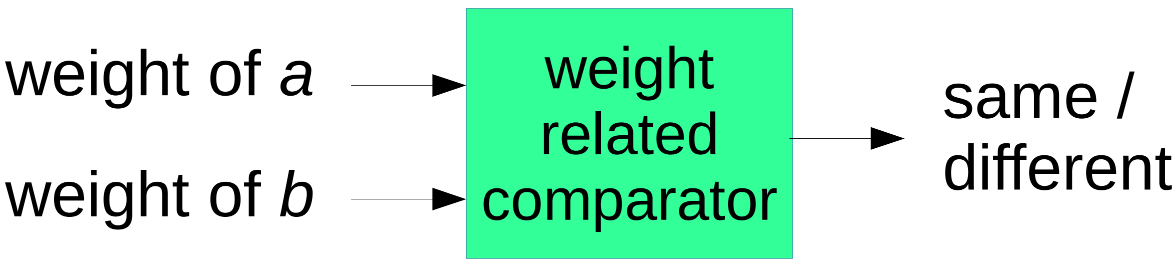
Comparison



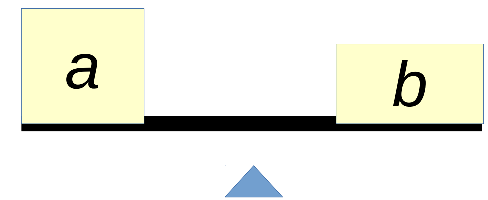
- Measuring instruments are both **experimental and information machines**
  → measurement results are pieces of information
- Measurement is based on **comparison**...
  → measuring instruments operate as comparators
- ... but **comparison is not enough for measurement**
  → a measurement result is not
  (1) the objects *a* and *b* have the same weight
  but
  (2) the weight of *a* is 2 kg

Standardization in measurement is mainly related to what is required to obtain (2) from (1)

From comparison to measurement



if same, then $W(a) = W(b)$

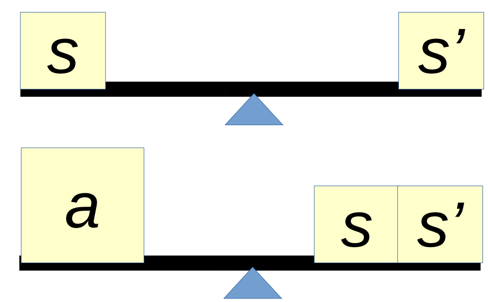


Let us choose two objects *s* and *s'* such that

$W(s) = W(s')$

and suppose that

$W(a) = W(s \oplus s')$

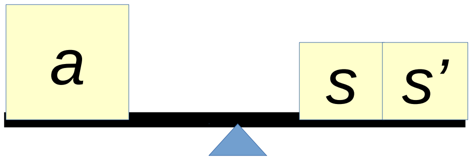


Then we can report that the weight of *a* is twice the weight of *s*:

$W(a) = 2\, W(s)$

Units and unit realization

We could even name the individual quantity *W*(*s*)
as, say, “geneva”, symbol g,
so that the result is *W*(*a*) = 2 g



and by definition *W*(*s*) = 1 g

We are thus adopting the individual quantity *W*(*s*) as a **unit**

In order to make comparisons leading to results “in genevas”
experimentally possible, at least one object *s*
that **materializes the unit** must be available

s is called a **measurement standard**

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

Some lexicon

Given $W(a) = 2$ g:

measurand: “quantity intended to be measured” (e.g., $W(a)$)

measurement result: “set of quantity values being attributed to a measurand together with any other available relevant information” (e.g., an interval of values about 2 g)

measured quantity value: “quantity value representing a measurement result” (e.g., 2 g)

measurement unit: “real scalar quantity, defined and adopted by convention, with which any other quantity of the same kind can be compared to express the ratio of the two quantities as a number” (e.g., g)

numerical quantity value: “number in the expression of a quantity value, other than any number serving as the reference” (e.g., 2)

[VIM]

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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 New York, 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 (current!) cases

In the International System of Units (Système International d'Unités, SI):

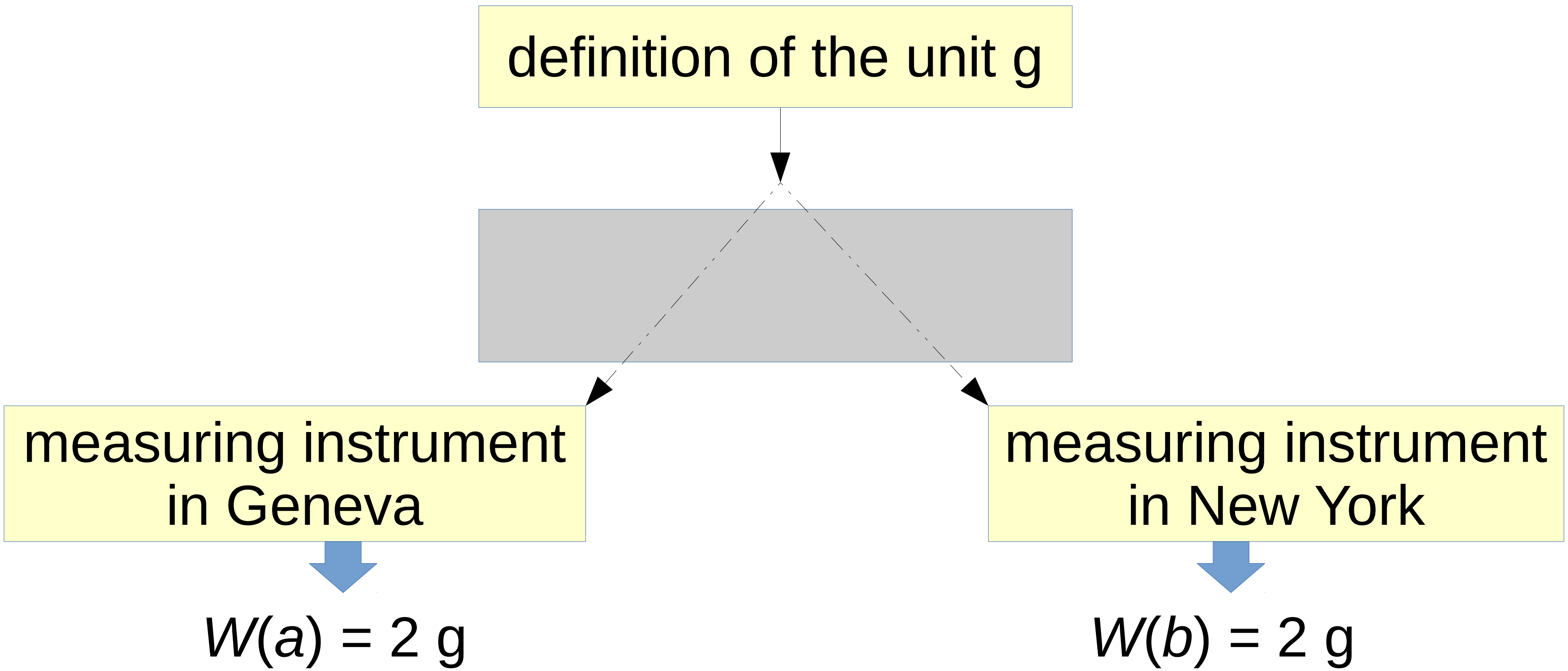
"The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram."
(*a definition referring to a concrete, individual object*)

"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 $W(a) = W(b)$

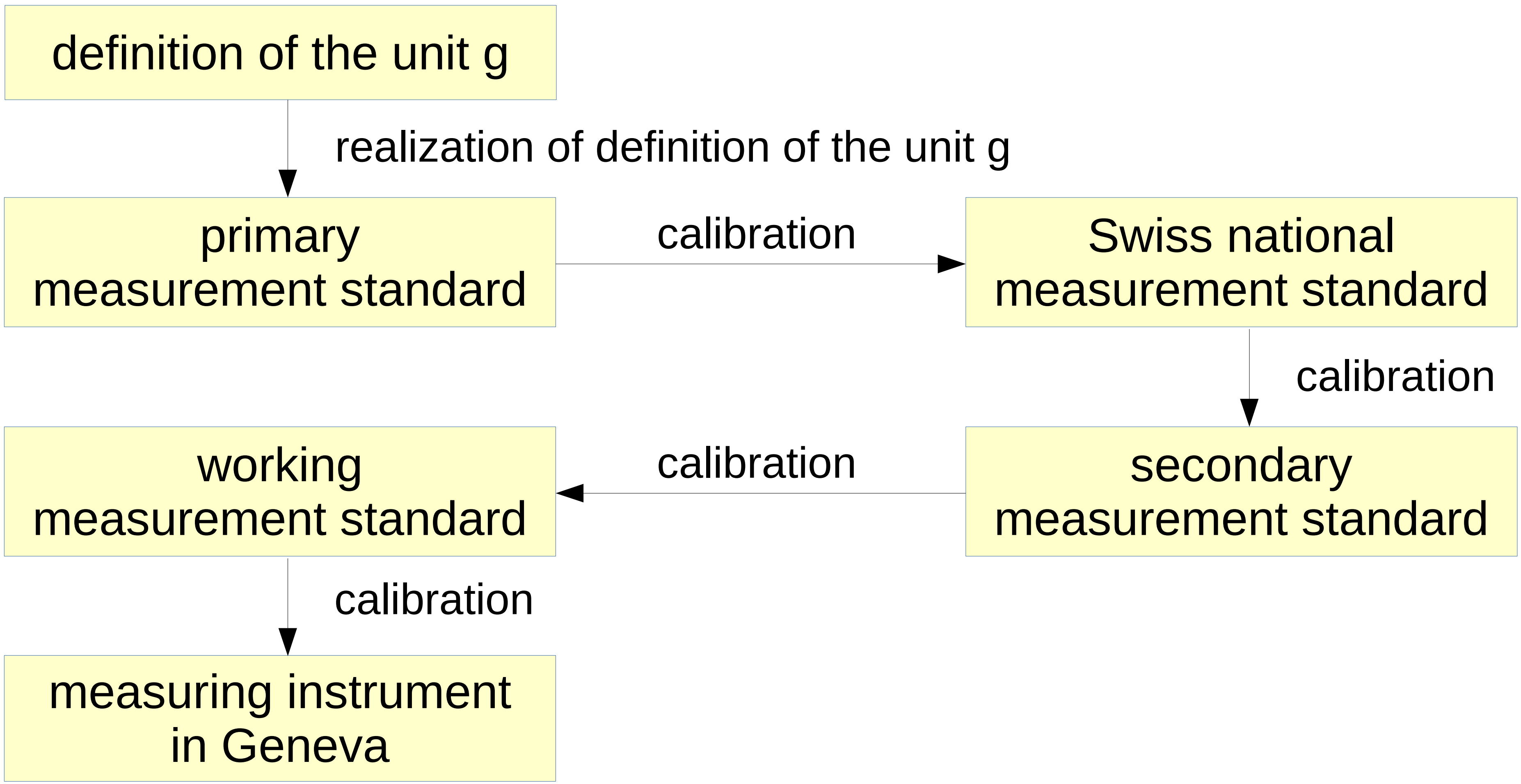
(i.e., that measurement results convey intersubjective information)

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

[VIM]

accessibility (“everywhere”)

Metrological traceability chain



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

[VIM]

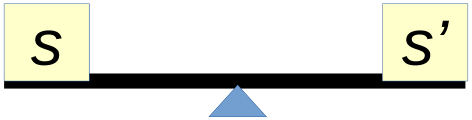
Calibration

An appropriate calibration is then a key condition
for the intersubjectivity of measurement results

Both measurement standards and measuring instruments
need to be calibrated

The principle of calibration of a measurement standard is simple:

1. it is known that $W(s) = 1$ g
2. it is experimentally assessed that $W(s') = W(s)$

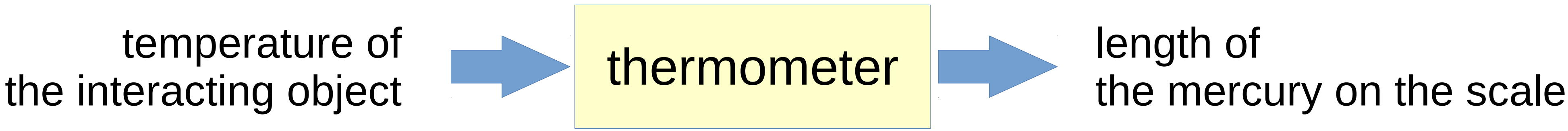


3. s' is calibrated against s by assigning $W(s') = 1$ g

accessibility (“everywhere”)

Calibrating a measuring instrument

Let us consider the simple case of a thermometer,
which physically operates as a **transducer**,
mapping variations of temperature (input) to variations of length (output):



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

Calibrating a measuring instrument

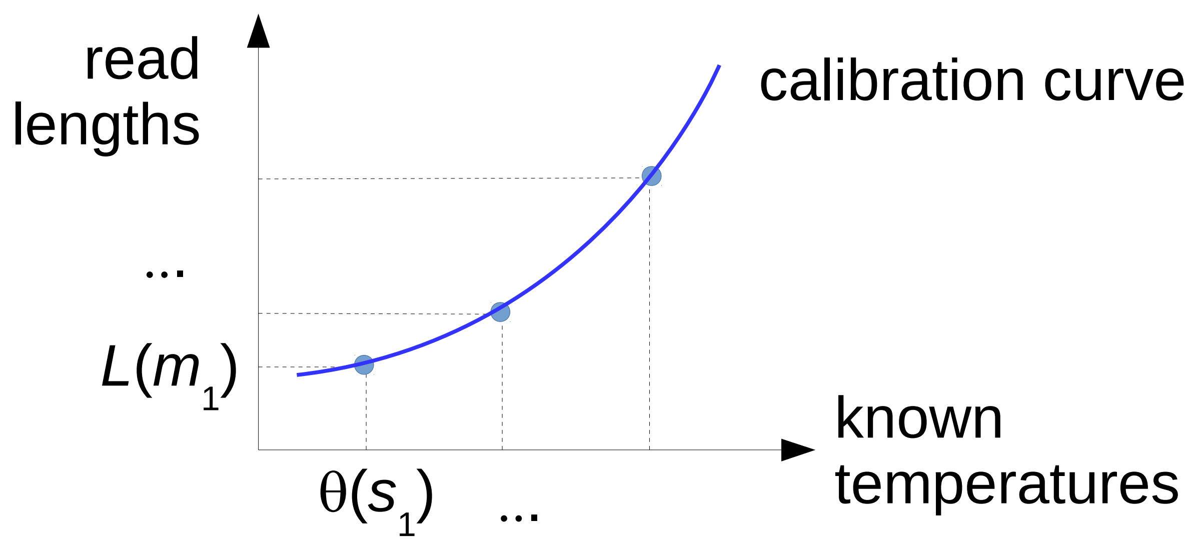
Let us assume that we can let the thermometer interact with **temperature standards**, so that:

known temperature $\theta(s_i)$ of a standard → thermometer → length $L(m_i)$ of the mercury in the scale

For each standard we obtain a pair

<known temperature $\theta(s_i)$, read length $L(m_i)$>

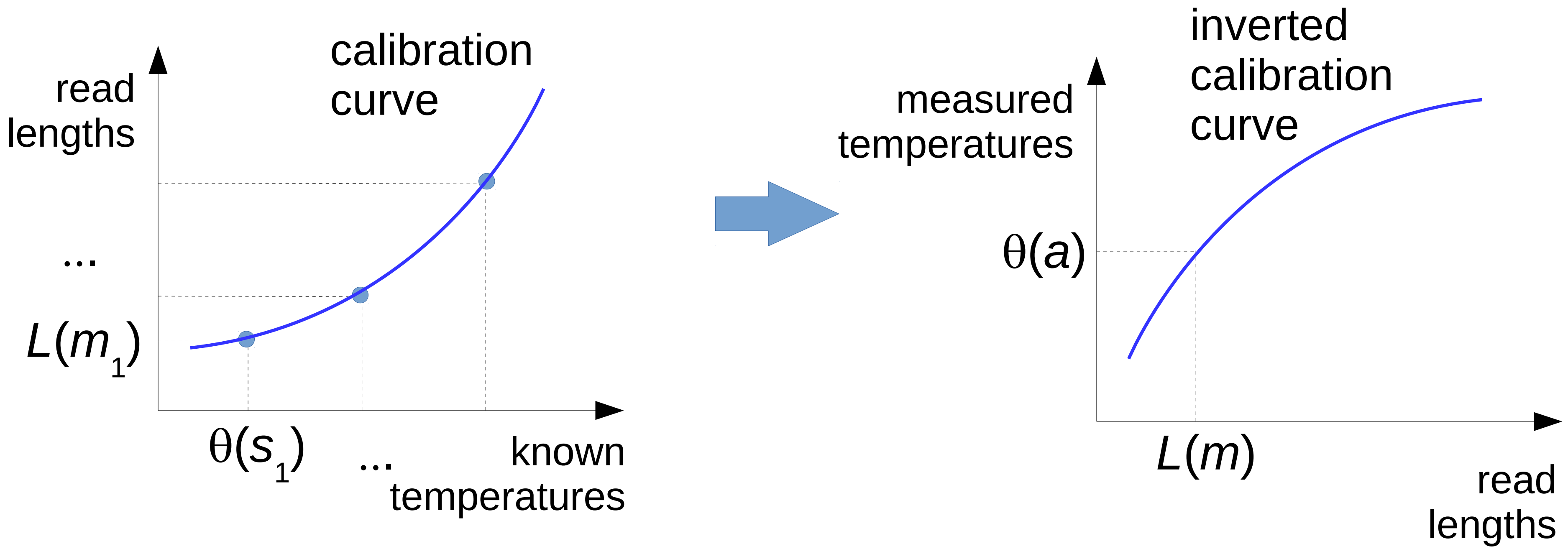
In a chart:



From calibration to measurement

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

calibration **measurement**



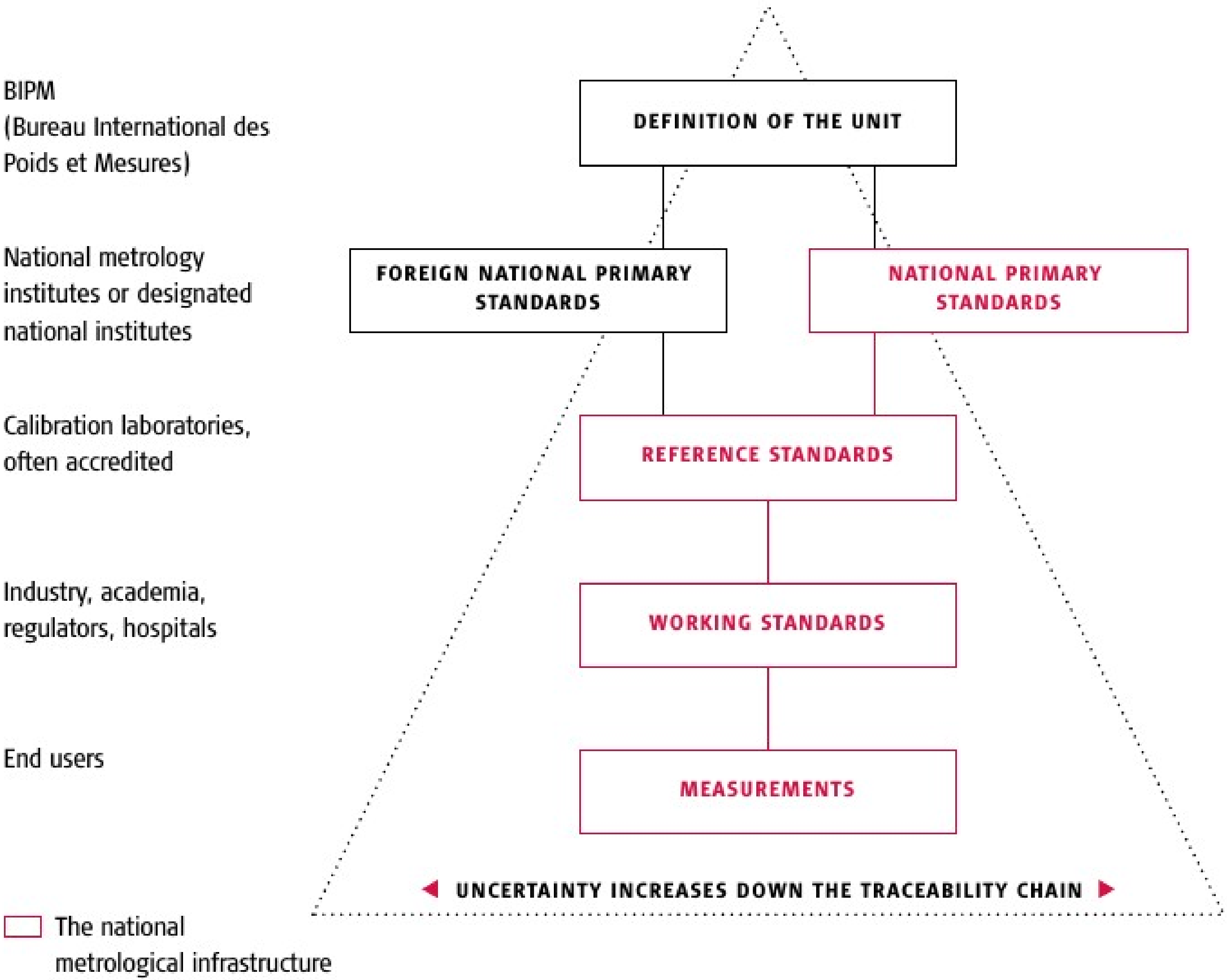
A fundamental concept: measurement uncertainty

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**

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:

$W(a) = 1.23456(3)$ u

meaning that we are uncertain of the last decimal digit:

the value might be in the interval 1.23456 ± 0.00003 u

(*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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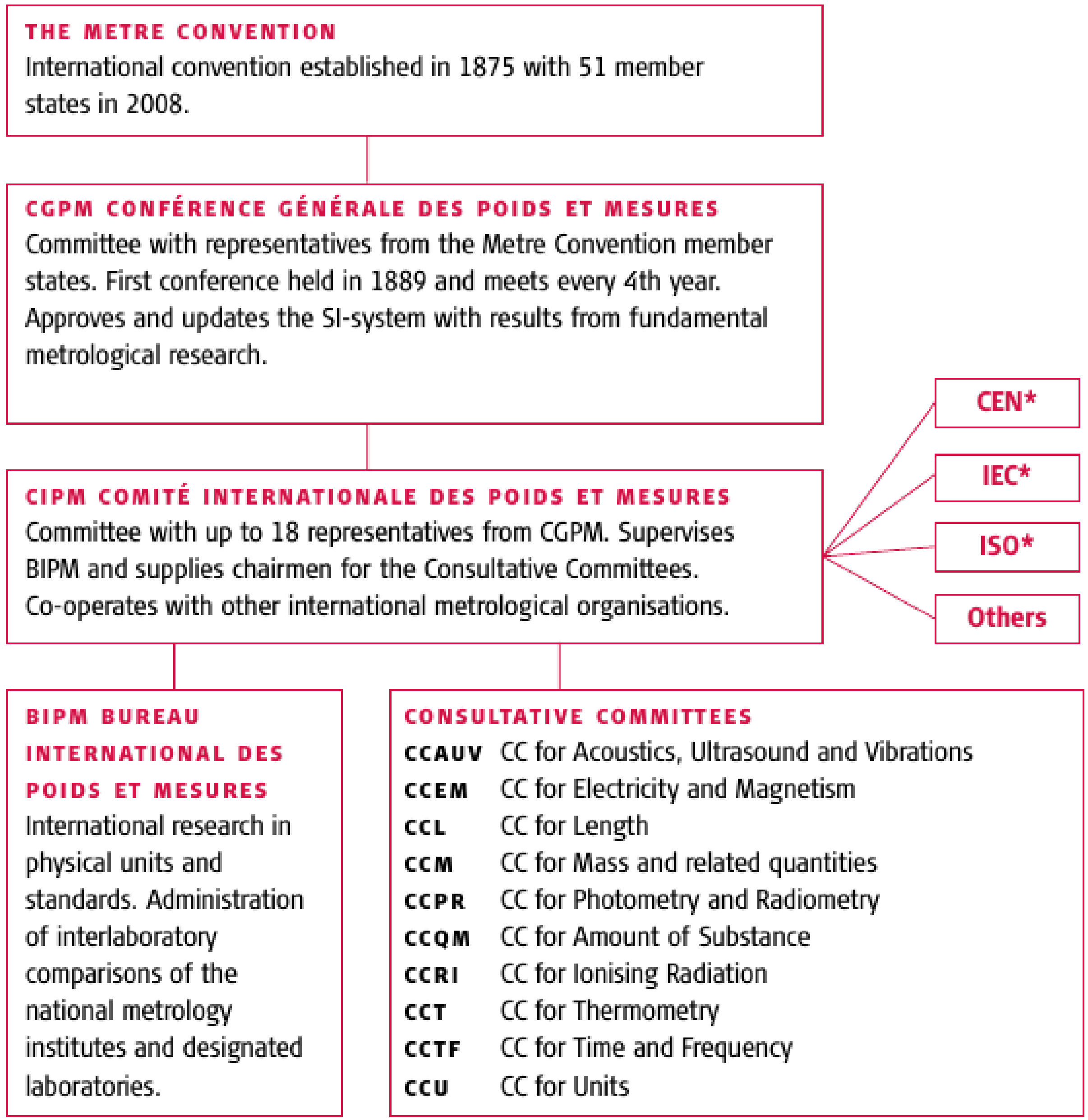
Standardization in measurement

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

1. Introduction: justification
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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]

The current state...

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 the new vision

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 of such units
- the distinction between base quantities/units and derived quantities/units
- each unit can be realized in different ways

- unit definitions are much harder to explain...

An example: the metre

Today:

“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”

Tomorrow:

“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
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Thanks for your kind attention

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