

# Metrology and standardization

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# My profile

Luca Mari (M.Sc. in physics; Ph.D. in measurement science) is full professor of measurement science at Università Cattaneo – LIUC, Castellanza (VA), Italy, where he teaches courses on measurement science, statistical data analysis, system theory.

He is currently the chairman of TC1 (Terminology) and the secretary of TC25 (Quantities and Units) of the International Electrotechnical Commission (IEC), and an IEC expert in the WG2 (VIM) of the Joint Committee for Guides in Metrology (JCGM). He has been the chairman of the TC7 (Measurement Science) of the International Measurement Confederation (IMEKO).

He is the author or coauthor of several scientific papers published in international journals and international conference proceedings. His research interests include measurement science and system theory.

# Some of my recent publications

- 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 Instr. Meas. Mag.*, 2014
- P.Micheli, LM, **The theory and practice of performance measurement**, *Manag. 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
- LM, A.Giordani, **Quantity and quantity value**, *Metrologia*, 2012
- LM, P.Carbone, D.Petri, **Measurement fundamentals: a pragmatic view**, *IEEE Trans. Instr. Meas.*, 2012
- A.Giordani, LM, **Measurement, models, uncertainty**, *IEEE Trans. Instr. Meas.*, 2012
- A.Giordani, LM, **Property evaluation types**, *Measurement*, 2012
- V.Lazzarotti, R.Manzini, LM, **A model for R&D performance measurement**, *Int. J. Production Economics*, 2011
- A.Frigerio, A.Giordani, LM, **Outline of a general model of measurement**, *Synthese*, 2010
- D.Macii, LM, D.Petri, **Comparison of measured quantity value estimators in nonlinear models**, *IEEE Trans. Instr. Meas.*, 2010

# This lecture

- Basic concepts
- In the last twenty years...

References [xyz] in the last slide

# The critical importance of measurement: some 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

# Metrology and standardization, then

What measurement can offer to standardization is quite clear

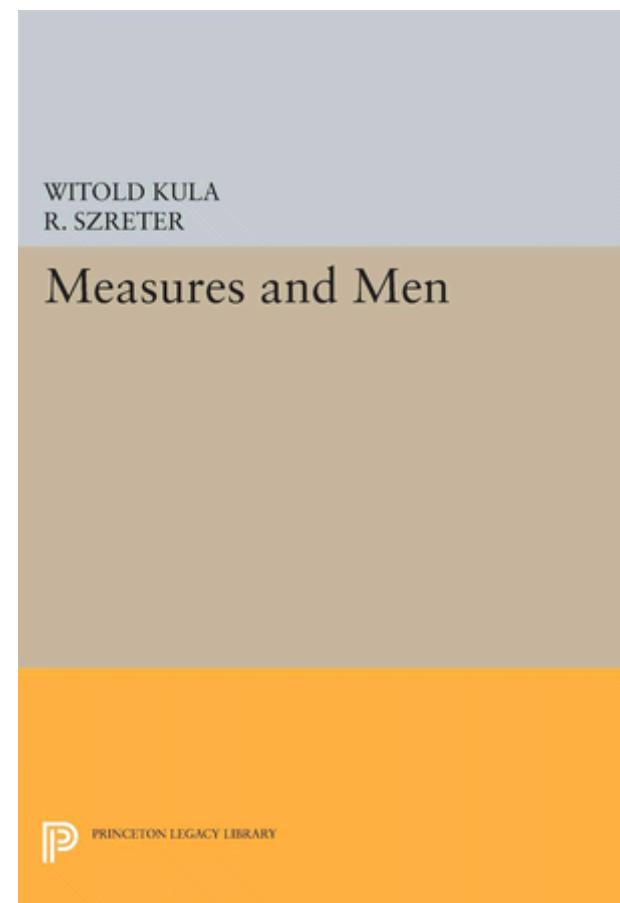
Less obvious is what measurement requires from standardization, and what should be standardized in measurement and why

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

# Measurement enables just society



The weight of an object is a fact that can be established independently of economical, political, religious, ... positions



[https://en.wikipedia.org/wiki/Lady\\_Justice](https://en.wikipedia.org/wiki/Lady_Justice)

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

How can measurement have this role?  
What is measurement?



# The basic features of measurement

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



**how can measurement results be  
objective and intersubjective?**

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

# Backgrounder: 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 **quantity value**, e.g., 2 kg

a simple **measurement result** being:

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

the weight of the object  $A$  is  
(or: is represented by; or: is expressed by) 2 kg

# Backgrounder: quantities and numbers

A relation such as:

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

can be interpreted as:

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

This is at the basis of the traditional Euclidean standpoint:

**numbers can be intended as ratios of quantities**

# Backgrounder: numbers

Of course, one can obtain a result such as:

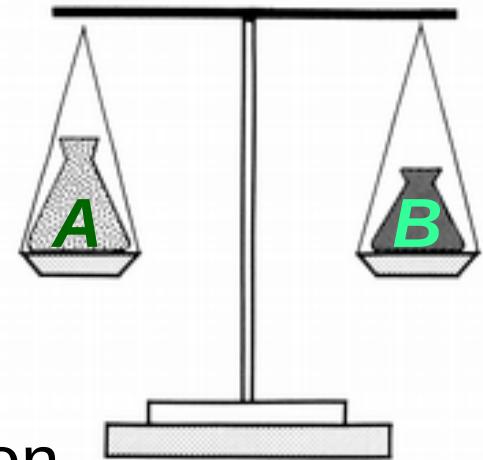
$$W(A) = 2 \text{ kg}$$

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 justice**

(measurement  $\neq$  quantification)

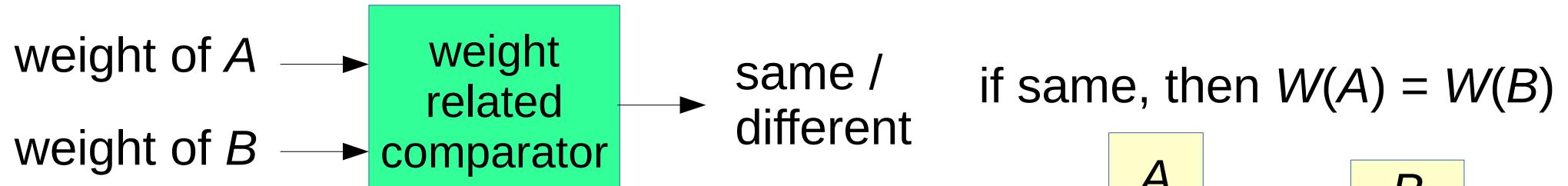
# Backgrounder: comparison



- Measuring systems are **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
  - (α) the objects A and B have the same weight  
but
  - (β) the weight of the object A is 2 kg

**Standardization in measurement is mainly related  
to what is required to obtain (β) from (α)**

# From comparison to measurement

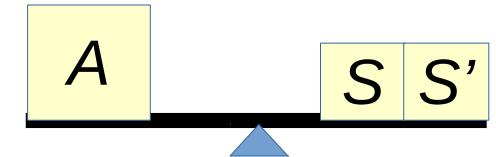
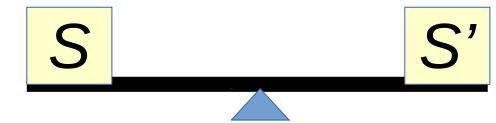
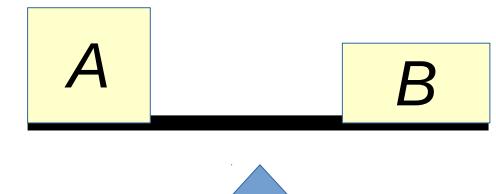


Let us choose two objects  $S$  and  $S'$  such that

$$W(S) = W(S')$$

and suppose that

$$W(A) = W(S \oplus S')$$



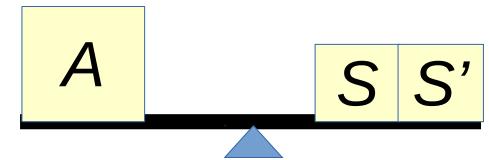
Then we can report that the weight of  $A$  is twice the weight of  $S$ :

$$W(A) = 2 W(S)$$

# Units and unit realization

We could even name the individual quantity  $W(S)$  as, say, “geneva”, symbol g,  
so that the result is  $W(A) = 2 \text{ g}$

and by definition  $W(S) = 1 \text{ g}$



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

In order to make comparisons leading to results “in genevas” experimentally possible, at least one object  $S$  that **realizes 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  $W(A) = 2 \text{ g}$ :

measurand: “quantity intended to be measured” ( $W(A)$ )

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” (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” (g)

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

# Intersubjectivity

The fundamental claim of measurement is that a sentence such as  
 $W(A) = 2 \text{ g}$

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 quantity)*

This implies that the quantity 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

# Unit definition



A significant example, the metre:

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

1.  
low stability  
no theory

2.  
fair stability  
almost no theory

3.  
maximum stability  
theory-laden

# Extreme (current!) cases

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

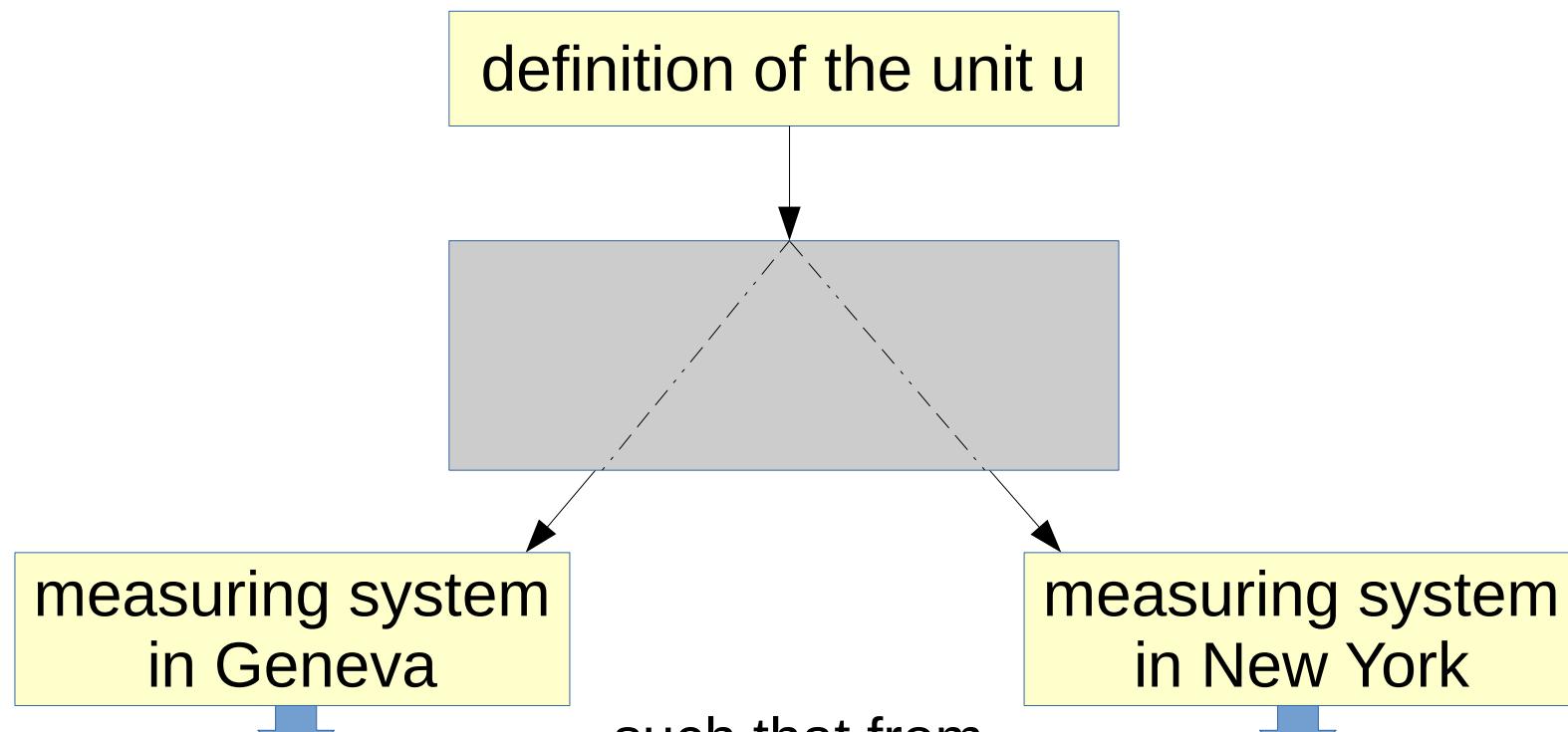
“The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.”

(*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  $2 \times 10^{-7}$  newton per metre of length.”

(*a definition referring to an abstract, ideal phenomenon*)

# Metrological traceability



we can safely infer that  
 $W(A) = W(B)$

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

[VIM]

# Calibration

metrological traceability:

“property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty”

[VIM]

definition of the unit u



realization of the unit u: primary measurement standard



working measurement standard



measuring system

metrological traceability chain:

“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 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?

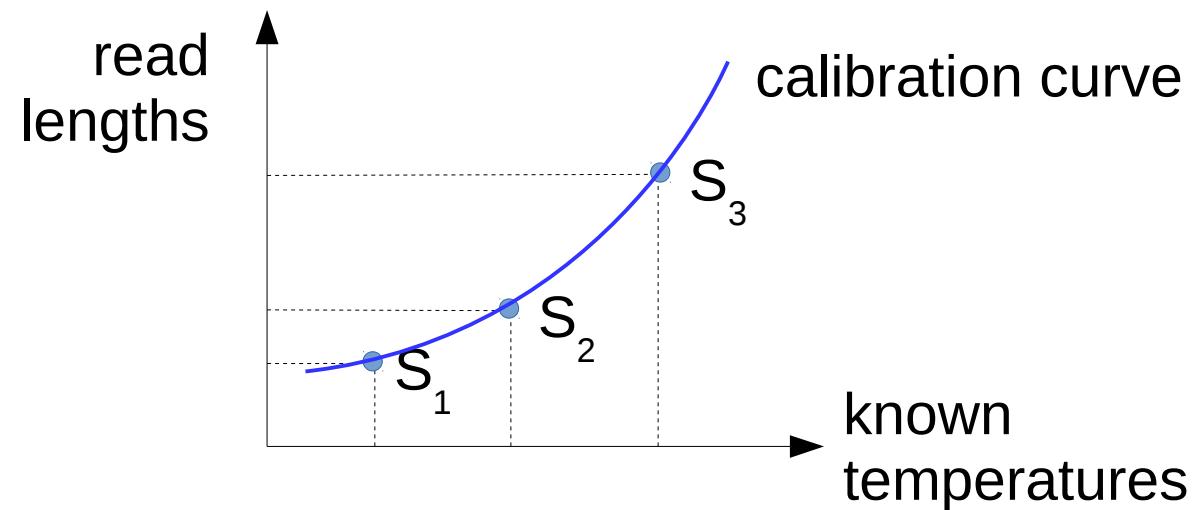
# Calibrating a measuring instrument

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



For each standard we obtain a pair <known temperature, read length>

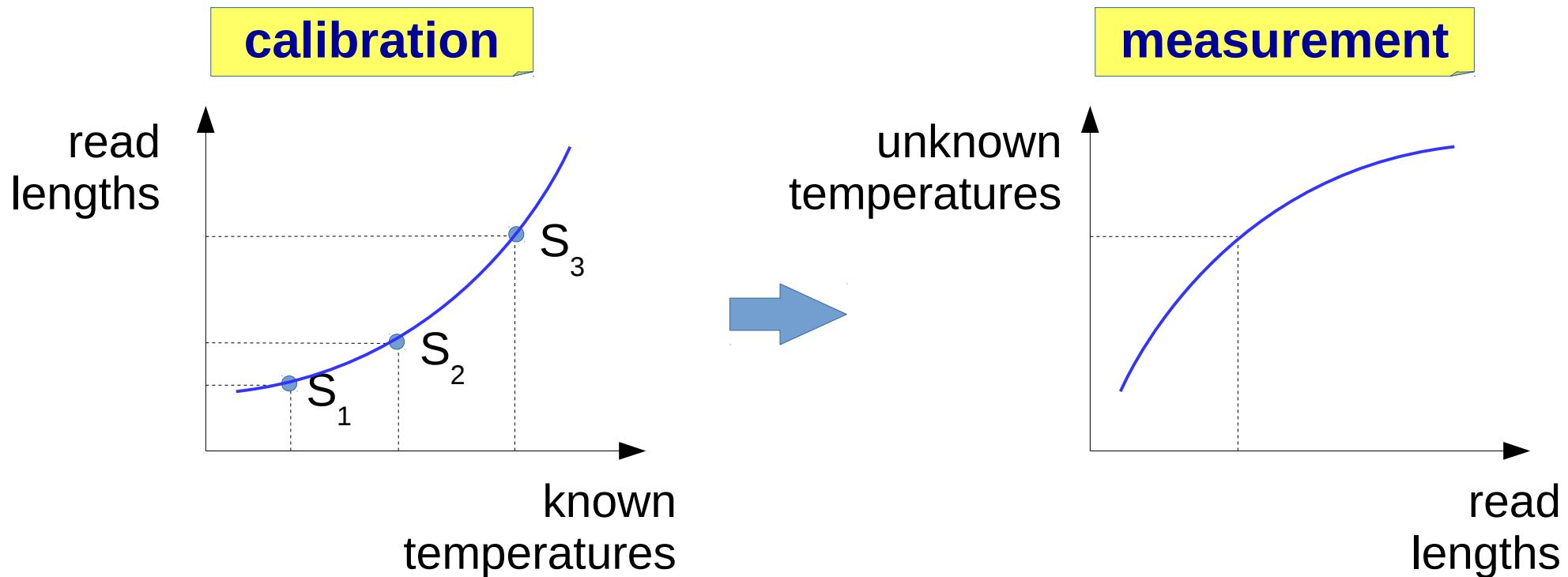
In a chart:



# 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**

**calibration and measurement results  
are generally affected by some uncertainty**

# The metrological system

BIPM  
(Bureau International des  
Poids et Mesures)

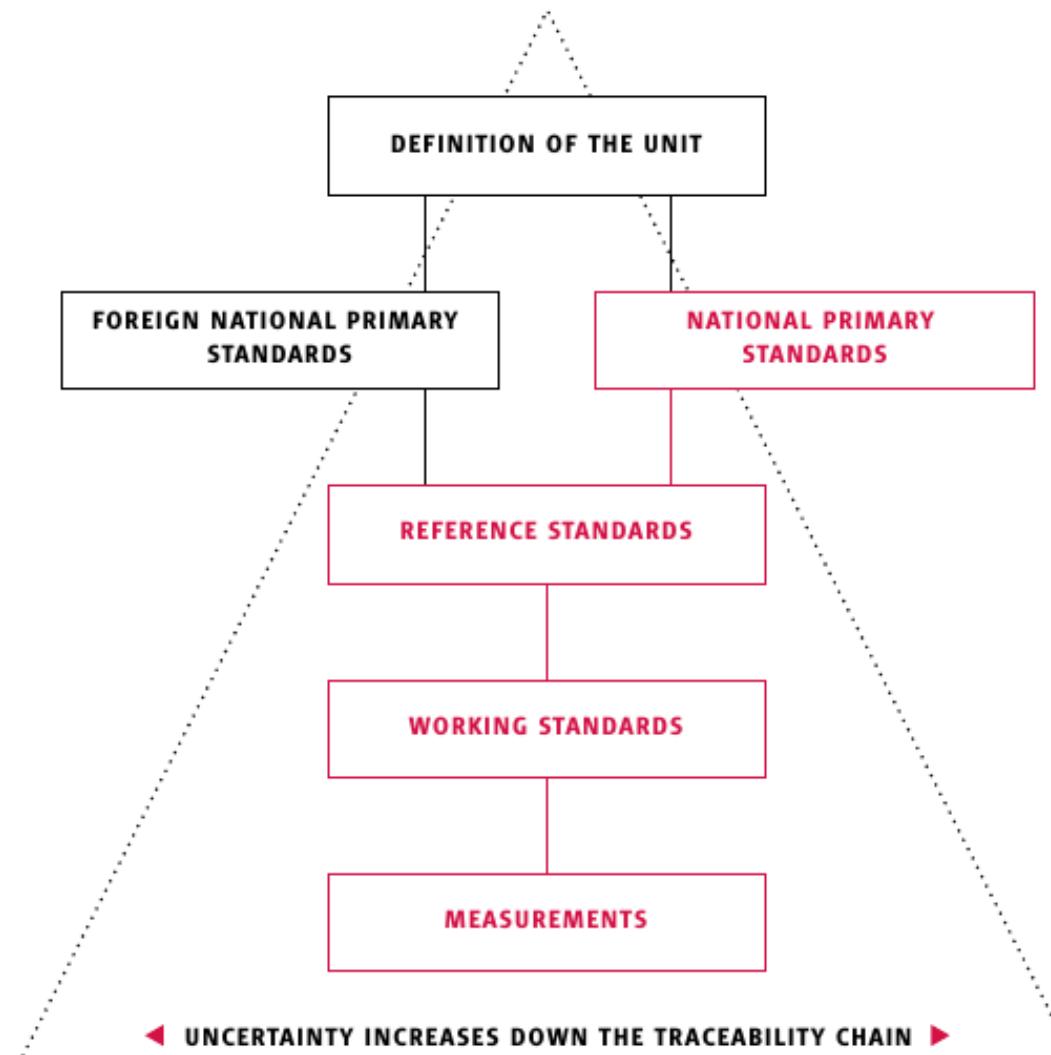
National metrology  
institutes or designated  
national institutes

Calibration laboratories,  
often accredited

Industry, academia,  
regulators, hospitals

End users

The national  
metrological infrastructure



# Measurement uncertainty

measurement uncertainty:

“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:

$$W(A) = 1.23456(3) \text{ u}$$

meaning that we are uncertain of the last decimal digit:

the value might be in the interval  $1.23456 \pm 0.00003 \text{ u}$

(*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**

# 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

## THE METRE CONVENTION

International convention established in 1875 with 51 member states in 2008.

## CGPM CONFÉRENCE GÉNÉRALE DES POIDS ET MESURES

Committee with representatives from the Metre Convention member states. First conference held in 1889 and meets every 4th year. Approves and updates the SI-system with results from fundamental metrological research.

## CIPM COMITÉ INTERNATIONALE DES POIDS ET MESURES

Committee with up to 18 representatives from CGPM. Supervises BIPM and supplies chairmen for the Consultative Committees. Co-operates with other international metrological organisations.

CEN\*

IEC\*

ISO\*

Others

## BIPM BUREAU

### INTERNATIONAL DES POIDS ET MESURES

International research in physical units and standards. Administration of interlaboratory comparisons of the national metrology institutes and designated laboratories.

## CONSULTATIVE COMMITTEES

- CCAUV** CC for Acoustics, Ultrasound and Vibrations
- CCEM** CC for Electricity and Magnetism
- CCL** CC for Length
- CCM** CC for Mass and related quantities
- CCPR** CC for Photometry and Radiometry
- CCQM** CC for Amount of Substance
- CCRI** CC for Ionising Radiation
- CCT** CC for Thermometry
- CCTF** CC for Time and Frequency
- CCU** CC for Units

[MIS]

# The (political and) legal side



Organisation Internationale de Métrologie Légale  
International Organization of Legal Metrology

ABOUT   PUBLICATIONS   STRUCTURE   CERTIFICATES   EVENTS   TECHNICAL WORK



Legal metrology and trade



What is legal metrology?

Legal metrology is the application of legal requirements to measurements and measuring instruments...

More info



Publications and Bulletin

The OIML develops model regulations, standards and related documents...

More info

[<https://www.oiml.org>]

# For Your Information...

29.3.2014

EN

Official Journal of the European Union

L 96/149

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**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]

- Basic concepts
- **In the last twenty years...**
  - MRA
  - JCGM: the GUM and the VIM
  - (expected) 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>]

# 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

# 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 a possible 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...

# 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**, 3<sup>rd</sup> ed, Euramet, 2008  
<http://www.euramet.org/index.php?id=mis>

[SIB] **SI Brochure: The International System of Units (SI)**, 8<sup>th</sup> 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)**, 3<sup>rd</sup> 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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