Bridging social and physical measurement: measurement is not scale construction; measurement is not quantification

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Outline

- Background materials
- Some basic hypotheses
- Two models of measurement
- Consequences

Abstract

Measurement is laden with stereotypes, of which one of most widespread is related to quantification: that is, while *qualities* such as beauty and wisdom may be basic elements of human knowledge, it is only on *quantities* that objective information is obtainable, and *measurement is the tool for quantification*. To evaluate the correctness of this position the two concepts should be independently defined and their relationship assessed.

Measurement is a designed-on-purpose process, and some conventionality and context-dependence in its characterization is unavoidable. On the other hand, that measurement is able to produce (at high degree) *objective* and *inter-subjective* outcomes is generally acknowledged, and it is unclear how quantification is related to such features and should specifically guarantee them.

My claim is that a *structural* interpretation throws some light on the issue, on the basis of the distinction between (a) scale construction, (b) measuring instrument calibration, and finally (c) measurement, the latter being performed in the two phases of (c1) information acquisition and (c2) information representation.

Understanding measurement in such a framework emphasizes how the basic functional role of stage (c1), i.e., the comparison of the property to be measured and a property realized by a measurement standard, is in fact independent of any algebraic constraints. Indeed it is performed identically for quantitative and non-quantitative properties. Furthermore, it is stage (c1) that crucially guarantees the objectivity of measurement results, depending on the good quality of the experimental design and realization of the comparison (this explains why the character of the measurer is traditionally depicted as the one of a good experimenter).

Complementarily, the inter-subjectivity of such results is related to their traceability to a widely accessible measurement standard, as guaranteed by the appropriate calibration of the measuring instrument. While the hypothesis that the property at stake is a quantitative one eases both scale construction and instrument calibration (as it is particularly obvious for additive quantities, whose scale can be constructed by a unit and the iterated application to it of the additive operation), the inter-subjectivity of results only depends on the good quality of the comparisons on which calibrations are based, and it is unaffected by the fact that the property is quantitative or not.

In synthesis, the hypothesis that the property to be measured is a quantity is beneficial for scale construction and instrument calibration but is specifically immaterial for measurement, thus showing the conventionality of the traditional assumption that only quantities are measurable.

This conclusion derives from a purely structural interpretation of measurement. Were the pragmatic position accepted that measurement is characterized as a process able to convey “objective enough” and “inter-subjective enough” information, this interpretation and its conclusion would be immediately applicable to the case of both physical and non-physical measurement, grounding their convergence towards a common conceptual framework.

Speaker profile

Luca Mari (M.Sc. in physics, 1987; Ph.D. in measurement science, 1994) is professor of measurement science, Università Cattaneo - LIUC, Castellanza (VA), Italy, where he teaches courses on measurement science, statistical data analysis, system theory. He heads the Ph.D. School and the Laboratory on RadioFrequency Identification (RFId) Systems at LIUC.

He is currently the chairman of the Technical Committee 1 (Terminology) and the secretary of the Technical Committee 25 (Quantities and Units) of the International Electrotechnical Commission (IEC), and an expert for the IEC in the Working Group 2 (International Vocabulary of Metrology) of the Joint Committee for Guides in Metrology (JCGM). He has been the chairman of the Technical Committee 7 (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.

My context: IMEKO

- TC1-Education and Training in Measurement and Instrumentation
- TC2-Photonics
- TC3-Measurement of Force, Mass and Torque
- TC4-Measurement of Electrical Quantities
- TC5-Hardness Measurement
- **TC7-Measurement Science**
- TC8-Traceability in Metrology
- TC9-Flow Measurement
- TC10-Technical Diagnostics
- TC11-Metrological Infrastructures
- TC12-Temperature and Thermal Measurements
- TC13-Measurements in Biology and Medicine
- TC13-Measurements in Biology and Medicine
- TC14-Measurement of Geometrical Quantities
- TC15-Experimental Mechanics
- TC16-Pressure and Vacuum Measurement
- TC17-Measurement in Robotics
- TC18-Measurement of Human Functions
- TC19-Environmental Measurements
- TC20-Energy Measurement
- TC21-Mathematical Tools for Measurements
- TC22-Vibration Measurement
- TC23-Metrology in Food and Nutrition
- TC24-Chemical Measurements

My context: JCGM

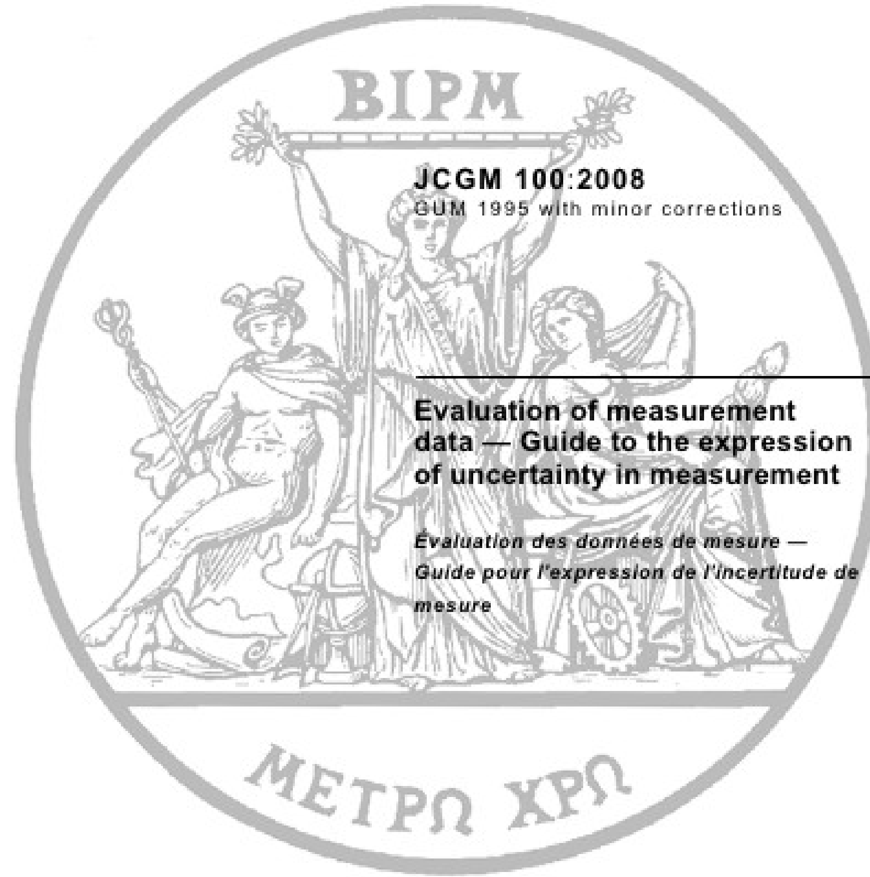
(JCGM) Joint Committee for Guides in Metrology:

- (BIPM) Int.l Bureau of Weights and Measures
- **(IEC) Int.l Electrotechnical Commission**
- (IFCC) Int.l Federation of Clinical Chemistry and Laboratory Medicine
- (ILAC) Int.l Laboratory Accreditation Cooperation
- (ISO) Int.l Organization for Standardization
- (IUPAC) Int.l Union of Pure and Applied Chemistry
- (IUPAP) Int.l Union of Pure and Applied Physics
- (OIML) Int.l Organization of Legal Metrology

JCGM guidance docs

the “VIM”

the “GUM”



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

Some of my recent publications

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

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

LM, V.Lazzarotti, R.Manzini, **Measurement in soft systems: epistemological framework and a case study**, *Measurement*, 2009

LM, **A computational system for uncertainty propagation of measurement results**, *Measurement*, 2009

LM, **On (kinds of) quantities**, *Metrologia*, 2009

LM, **The problem of foundations of measurement**, *Measurement*, 2005

LM, **Epistemology of measurement**, *Measurement*, 2003

LM, **Beyond the representational viewpoint: a new formalization of measurement**, *Measurement*, 2000

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- Some basic hypotheses / backgrounder
- Two models of measurement
- Consequences

Some basic hypotheses

*(arguing about **measurement** might be important)*

Being an infrastructural, widespread activity, performed by human beings since millennia, measurement is laden with myths...

… hence some analyzes aimed at de-mythologizing it might be useful

(the position that the only open scientific issues about physical measurement relate to quantum physics *is just wrong*)

Some basic hypotheses (2)

(arguing about measurement ***as experiment*** *might be important)*

... by difference with respect to positions such as:

«The theory of measurement is difficult enough without bringing in the theory of *making* measurements» [Kyburg, Theory and measurement, 1984, p.7]

«We are not interested in a measuring apparatus and in the interaction between the apparatus and the objects being measured. Rather, we attempt to describe how to put measurement on a firm, well-defined foundation»

[Roberts, Measurement theory, 1979, p.3]

(this is why I will try to avoid the term “measurement *theory*”)

Some basic hypotheses (3)

*(arguing about measurement **models** might be important)*

Measurement is an information production process

such as description, judgment by experience, and guess

But measurement is customarily considered conveying *valid and reliable* information

(in some specific sense to be further discussed)

and indeed some more resources are usually devoted to perform measurement than, e.g., guess

→ **What is the source / reason of this claim?**

Some basic hypotheses (4)

*(arguing about measurement might be important **here**)*

‘measurement’ appears to be, unfortunately,
an ambiguous concept
differently conceived in different scientific and technical fields

In particular, the (usually implicit and somewhat tautological)
characterization for physical quantities
– measurement is the process performed by
(physical device properly operated as) a measuring instrument –
is useless in the case of non-physical properties

→ **Can this multiplicity be reconciled?**

My pragmatics here

In facing new challenges in complex scenarios, physical/engineering measurement is changing and a new paradigm is (plausibly) emerging

(some hints: the emphasis on the role of models in measurement and on measurement uncertainty)

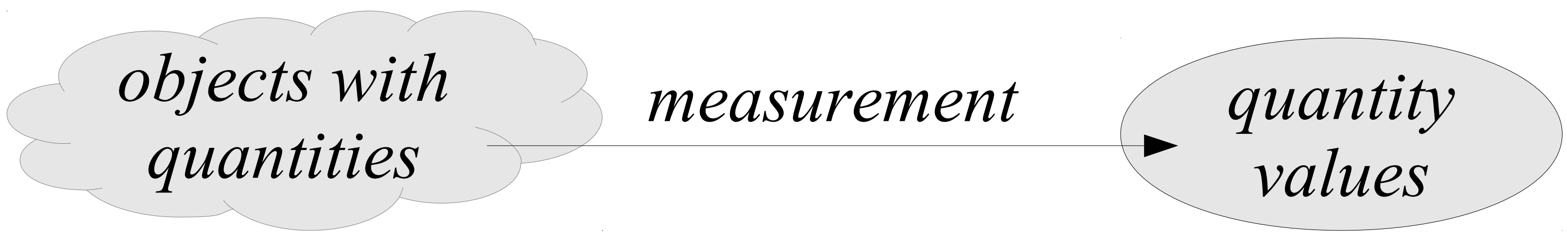
This might generate new opportunities in understanding the (complex) relations between “soft” (social) and “hard” (physical) measurement

→ **Let us explore these relations together...**

Backgrounder

A few basic concepts and terms (*simplest version, no uncertainty*):

- given an **object** (phenomenon, event, process, ...)
- having a **quantity** (attribute, property, ...)
- measurement is a **process** (operation, activity, ...)
- performed on the object to produce a **quantity value**
- called the **measurement result**
- and interpreted as conveying information on the quantity intended to be measured, the **measurand**



Measurement is a quantity representation process

Backgrounder (2)

In a measurement-related model:

- **general quantities** are taken into account of some objects (*e.g., length, for tables but not for liquids*)
- a general quantity of an object is an **individual quantity** (*length of a given table*)
- a measurement problem is about a general quantity (*measuring length*)
- measurement is performed on individual quantities (*measuring the length of this table*)
- a general quantity is characterized by a set of quantity values (*positive real numbers with a unit for length*)
- an individual quantity is represented by a quantity value (*the length of this table is* 2.34 m)

Backgrounder (3)

These assumptions lead to a functional model where:

[**ontological** side]

- a general quantity Q is interpreted as a function,
- whose domain is a set $\{objects\}$ of objects
- and whose range is a set $\{q\}$ of individual quantities

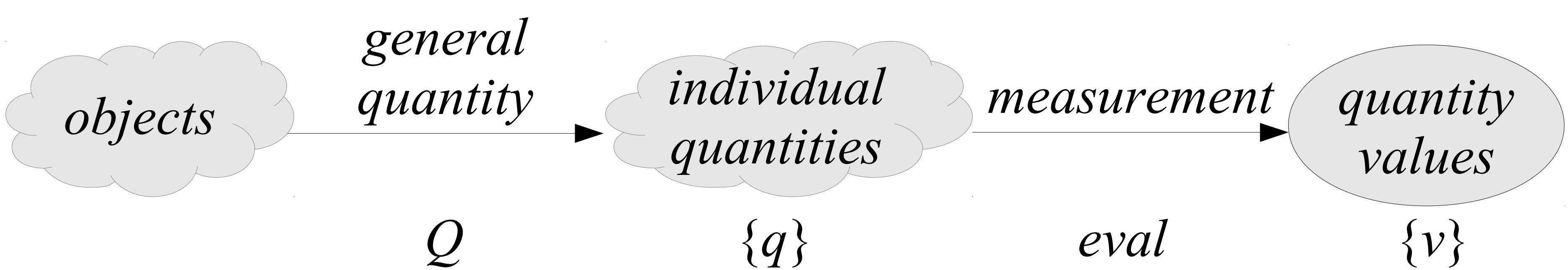
$$Q : \{objects\} \rightarrow \{q\}$$

[**operational** side]

- measurement assigns a value to (“evaluates”) an individual quantity:

$$eval : \{q\} \rightarrow \{v\}$$

where $\{v\}$ is a set of quantity values



Backgrounder (4)

In the light of this structure:

let us consider the Maxwell's equation (the basis of dimensional analysis):

individual quantity = number · unit

Here the mapping $eval : \{q\} \rightarrow \{v\}$ remains implicit

(a trace of the metaphysical hypothesis that measurement "mirrors" reality?)

so that instead of:

$$eval(length(this\ table)) = 2.34\ \mathrm{m}$$

the simpler version:

$$length(this\ table) = 2.34\ \mathrm{m}$$

is customarily used

Backgrounder (5)

This functional model involves three comparison relations:

- between individual quantities
  (e.g., the length of object i is equal to the length of object j)

$$\alpha\text{–comparison / }\alpha\text{–equality: } q_i =_\alpha q_j$$

→ this is an **experimental comparison** (*but not a measurement*)

($q_i =_\alpha q_j$ is sometimes written $q_i \approx q_j$ to emphasize its experimental nature)

- between quantity values
  (e.g., $2.34\ \mathrm{m}$ is equal to $7.67...\ \mathrm{ft}$)

$$\beta\text{–comparison / }\beta\text{–equality: } v_i =_\beta v_j$$

→ this is a **formal equality** (*surely not a measurement*)

- between an individual quantity and a quantity value
  (e.g., the length of this object is equal to $2.34\ \mathrm{m}$)

$$\gamma\text{–comparison / }\gamma\text{–equality: } q =_\gamma v$$

→ this is an **evaluation** (*e.g., a measurement*)

Backgrounder: synthesis

experimental comparison

individual quantities

evaluation *evaluation*

$$\begin{tikzcd}[column sep=huge] \text{length of object } i \arrow[r, leftrightarrow, "=_\alpha"] \arrow[d, "=_\gamma"'] & \text{length of object } j \arrow[d, "=_\gamma"] \\ 2.34\text{ m} \arrow[r, leftrightarrow, "=_\beta"] & 7.67\ldots\text{ ft} \end{tikzcd}$$

quantity values

informational equality

where the γ–equality $q =_\gamma v$ is in fact a mapping $eval(q) = v$

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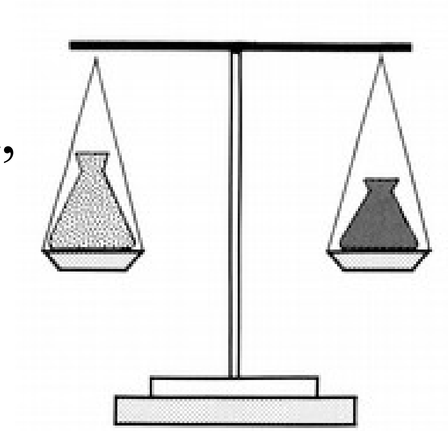
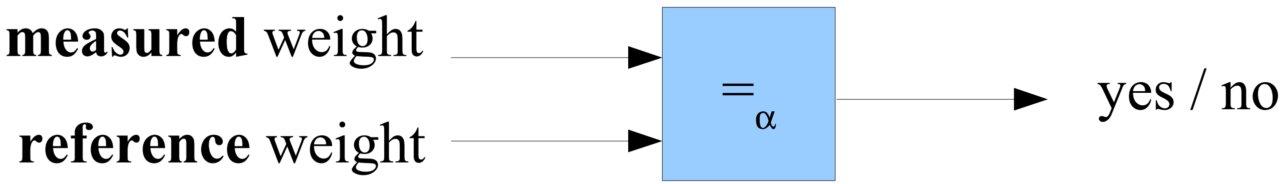
The “basic” model of measurement

object under measurement,
having a quantity q
(*the measurand*)

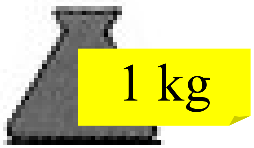


object realizing
a reference quantity r

Here the measuring instrument is just an α-comparator:



where a value to the reference weight has been assigned:



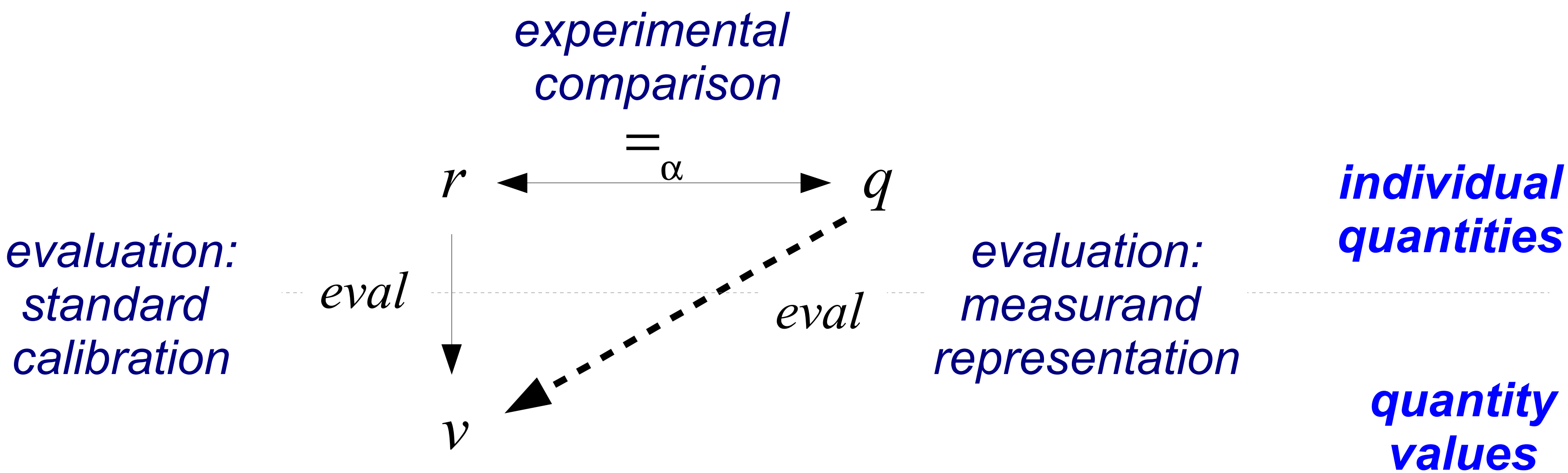
eval$(r) = v$ (i.e., $r =_\gamma v$):

an operation called “standard calibration”

The “basic” model of measurement (2)

Measurement is an **inferential process** such that:

if $r =_{\alpha} q$	(experimental comparison)
and $eval(r) = v$	(standard calibration: *prior* evaluation)
then $eval(q) = v$	(measurand representation: *posterior* evaluation)



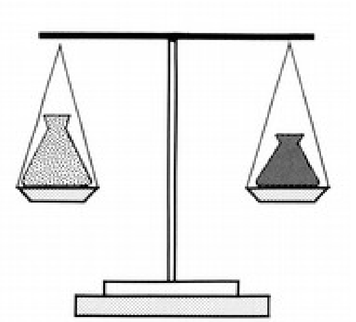
The “basic” model of measurement: synthesis

The inference: IF experimental comparison
AND standard calibration (*prior* evaluation)
THEN measurand representation (*posterior* evaluation)

is critically based on:

- the **synchronous availability** of the object under measurement and the standard which realizes the reference
- the **stability** of the standard, since the standard calibration and the experimental comparison are performed at different times

The “basic” model of measurement: shortcomings



This procedure requires the availability of:

- measurement standards when measurement is performed (“direct” comparison actually means *synchronous* comparison)
- references of the same order of magnitude of the measurand
- a device able to compare quantities of that order of magnitude

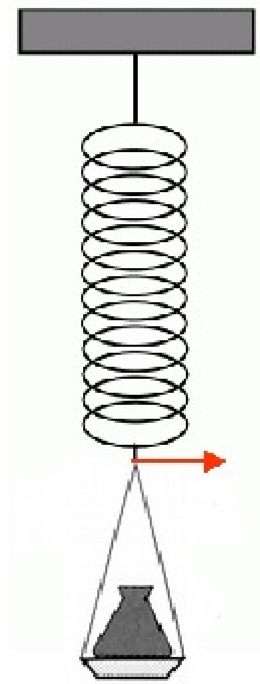
The “standard” model of measurement

These shortcomings are overcome when measurement is performed according to a different, and actually much more widespread, procedure

The measurand is applied to a device which produces another quantity in response:

$$\text{weight} \longrightarrow \boxed{\tau} \longrightarrow \text{length}$$

transducer



It is then assumed that such “output quantity” (traditionally called the “indication”) is mapped to a value

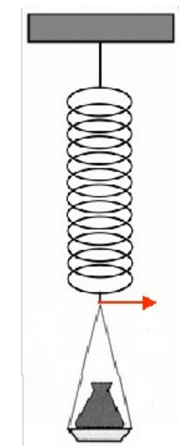
$$\text{weight} \longrightarrow \boxed{\tau} \longrightarrow \text{length}$$

$$\text{length} \downarrow \text{length value}$$

and that this value conveys sufficient information on the measurand value

The “standard” model of measurement (2)

The core concept is the “divide and conquer” strategy



The given measurement problem P (to measure a weight) is split into three subproblems:

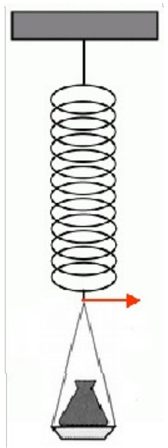
1. convert P to another measurement problem P’
   (transduce weight to length)
2. solve P’
   (measure length)
3. use the solution to P’ to solve P
   (obtain a weight value from the length value)

$$\begin{tikzcd}
q \arrow[r, "P1"] \arrow[d, dashed, "P"'] & q' \arrow[d, "P2 = P'"] \\
v & v' \arrow[l, "P3"]
\end{tikzcd}$$

The structure of measurement

Let us analyze the structure of the new problem:

$$\begin{tikzcd} q \arrow[r] \arrow[d, dashed, "P"'] & q' \arrow[d, "P'"] \\ v & v' \arrow[l] \end{tikzcd}$$



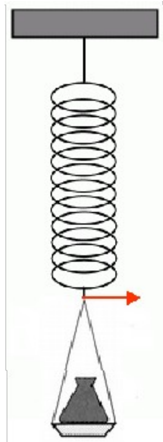
P' is supposed to be "primitively solvable", or at least simpler than P, so to avoid a never-ending recursion

… and indeed the output quantity q' is:

- traditionally the position of a needle against a scale of marks
- today customarily a sampled and quantized electrical quantity
- often a quantity that can be counted

The structure of measurement (2)

$$\begin{tikzcd} q \arrow[r] \arrow[d, dashed, "P"'] & q' \arrow[d, "P'"] \\ v & v' \arrow[l] \end{tikzcd}$$



The experimental stage is a transduction, not a comparison

The mapping $v' \rightarrow v$ is expected to be the "informational inverse" of the transduction

How to obtain it?

Instrument calibration

A set of measurement standards is available such that each of them:

- realizes a reference quantity r
- is associated with a given quantity value v
- is transduced to an output quantity q' and then mapped to an output quantity value v'

Then the mapping κ ("calibration function") can be built for each value realized by a measurement standard:

$$\begin{tikzcd} r \arrow[r] \arrow[d] & q' \arrow[d] \\ v \arrow[r, dotted, "\kappa"] & v' \end{tikzcd}$$

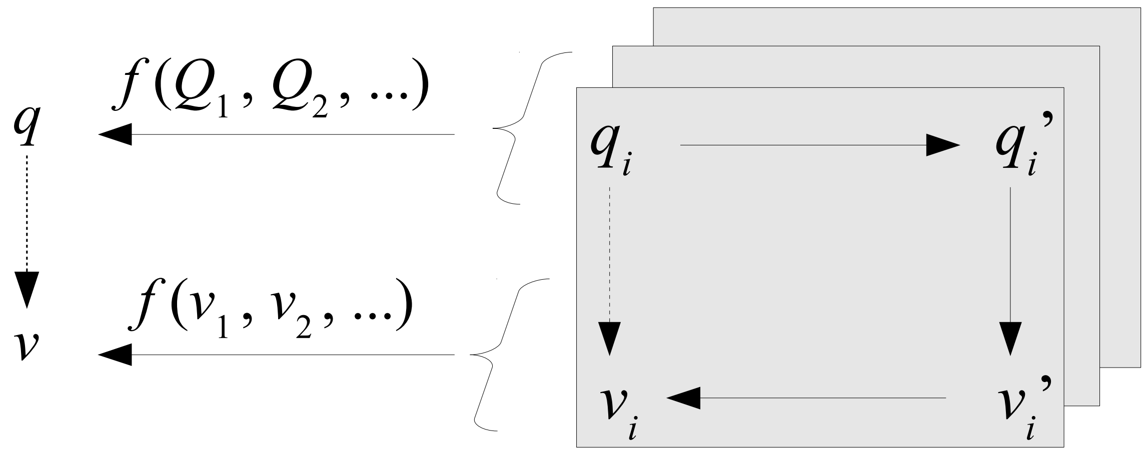
and it is assumed to be invertible

Measurands as input quantities

The model $q \rightarrow q'$ is a simplification, because it assumes that the input quantity to the transducer is actually the measurand

In a more general case, the measurand q might be not the input quantity of a transducer, but is dependent, through a function f, on one or more "(partial) indicator" quantities q_i that can be transduced (or whose values are somehow known)

The whole measurement process is then:



where the measurand q is here properly "a construct", characterized by the function f and possibly accepted as "non-observable"

The "standard" model of measurement: synthesis

Measurement is an **inferential process** such that:

the inference: IF transduction and mapping to output quantity values
AND standard calibration
AND transducer calibration
THEN measurand representation

is critically based on:

- the **stability** of the transducer, since the transducer calibration and the transduction are performed at different times

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The “basic” and the “standard” models: remarks

According to both models measurement is an **inferential process**
(here presented in the simplified version where accuracy is assumed and measurement uncertainties are not taken into account)

In this inferential process:

- **nothing requires quantification / additivity**:

  → the procedure operates identically in the ordinal and even in the nominal case

- **nothing implies the comparison / the transduction to be performed by a physical device or relatively to physical properties**:

  → in principle, the procedure operates identically for non-physical properties

Measurement and more

- **Scale construction**,
- **Measuring instrument calibration**, and
- **Measurement**

should be acknowledged to be as distinct processes

Then the fact that the property under consideration is a quantity:

- is a relevant information for scale construction
- is a convenient situation for instrument calibration
- is just immaterial for measurement

Epistemic features of measurement

Measurement results are supposed to convey information:

- **specific to the measurand**, and independent of any other property of the object or the surrounding environment, which includes both the measuring system and the subject who is measuring:
  → it is a requirement of **objectivity**, depending on the good quality of the experimental design and realization of the comparison / transduction performed by the measuring instrument
- **interpretable in the same way by different users** in different places and times, and therefore expressed in a form independent of the specific context and only referring to entities which are universally accessible

  → it is a requirement of **inter-subjectivity**, depending on the good quality of the comparisons on which standard and instrument calibration are based

Neither objectivity not inter-subjectivity depend on quantification

Measurement of non-physical properties

Nothing in this presentation implies the physical nature of measurands
Hence this analysis and its conclusions seem to be applicable also to non-physical properties

Nevertheless, some differences (typically) remain, at least:

1. Physical quantities are mutually related by physical laws; this allows:
   - minimizing primitive ("purely operational") concepts
   - cross-validating measurand definitions
   - cross-checking measurements results
2. A global metrological infrastructure is well established for physical quantities
3. The measurement of physical properties is a purely descriptive process (no Hawthorne effect...)
4. Physical properties have been measured since millennia

Bridging social and physical measurement: measurement is not scale construction; measurement is not quantification

Thank you for the kind attention

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