Measurement: the social spread of knowledge

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This paper is devoted to introducing measurement as a process aimed at producing knowledge that is socially shareable. Some subjects of the paper are the metrological system, metrological traceability, and calibration as tools to guarantee the intersubjectivity of measurement information.

Introduction

As introduced in the previous paper of this series [1], measurement aims at producing data, and then information, and then knowledge, about empirical properties of objects (we are using the term “object” in the generic sense of anything that has properties, thus including physical bodies, systems, phenomena, processes, and so on – along the same line, ISO terminological standards define ‘property’ as “feature of an object” [2]). In a semiotic framework [3], data may be accepted as something that is given, thus according to the meaning of the Latin term “datum”, what in English is sometimes called “evidence”. But data is only about the recognition of differences: it is this, and it might have been that: hence, a binary digit is the simplest case of data. It becomes information if it is referred to something (e.g., 0 stands for “no” and 1 for “yes”), and then possibly knowledge, if the information is embedded in a context and acknowledged to have a usefulness. Given that measurement data originates from and is about empirical sources, such a process of interpretation and contextualization cannot be taken as evidence in turn, and this generates a substantial issue of quality of the related information and knowledge [3].

This happens even in the case of simple measuring instruments, like an alcohol thermometer (a lexical note: we treat here “measuring instrument” and “measuring system” as synonyms, and use only the former). When operated according to the expected procedure, the thermal contact of the thermometer with the object under measurement makes the alcohol flow in the tube and its upper surface reach a position, more or less aligned to an etched mark. The instrument is designed to make the identification of the mark as unproblematic as possible, to allow us to treat the identified mark as evidence, and therefore an example of measurement data. For sure, some reading mistakes could always be made, but that the alcohol reached a given position is something that may be taken for granted. It should be clear that there is nothing special in this example: were, as another example, the thermometer based on a thermocouple, the instrument output would be a voltage instead of a position, but the structure of the arguments that follow would remain the same.

Such a physical transduction is supposed to causally connect the temperature of the object to the position of the upper surface of the alcohol in the tube. Hence, this setup allows us to interpret alcohol positions as *standing for* object temperatures, and therefore conveying information on them: accordingly, while the observation that the alcohol reached, say, the twenty-third mark is a *measurement data*, reporting such a mark as referred to the temperature that triggered the transduction, thus as

temperature of a given body → twenty-third mark of a given thermometer (1)

is an example of conveyed *information*, where in fact the arrow has to be meant as something like "is represented by". This process, called *pre-measurement* in [4], is structurally straightforward but has the obvious drawback that its results are not transferable, since they convey information that is correctly interpretable.

- only in reference to the given instrument, thus implying that the information about the temperature produced by different instruments is not comparable, and
- only under the condition of stability of the instrument, so that any change in its transduction behavior makes again the produced information not comparable.

Of course, the usual strategy is instead to report measurement results on a public scale of the measured property, as for example obtained in reference to degrees Celsius or kelvin in the case of temperature, and this offers at least two key benefits, as it produces information

- that is interpretable independently of the instrument by means of which it was generated, and
- that can be reported as a comparison, and in particular as an equation, between the measurand and a measured value.

Indeed, as discussed in [1], a *Basic Evaluation Equation* [5] like

temperature of a given body = 23.4 °C (2)

states that the temperature of the body and 23.4 °C are the same temperature identified (or presented, or known) in two different ways, as the property of an object and as a function of a unit, an interpretation that surely does not hold in the case of relation (1), given that the temperature of the body can be represented by a given mark of a given thermometer, but surely a temperature and a position cannot be the same quantity.

If the transition from relation (1) to equation (2) seems to be an easy achievement, it is because the worldwide metrological system works effectively, in its scientific, technological, and organizational layers that connect the instrument-independent public scale of temperature and the instrument-related local scale of positions. And it is because for most of us in most situations, the process that allows to convey measurement information using equation (2), instead of relation (1), may remain hidden in a black box. Nevertheless, what is inside the black box is complex, and deserves our attention: the present paper is devoted to this, and therefore to the conditions that make measurement able to produce information that is *intersubjective*, so that different subjects in different contexts are able to interpret it in the same way. Concretely, if for example the temperature of a body in New York is measured to be 74.1 °F and the temperature of a body in Paris is measured to be 23.4 °C, we explore here the conditions that allow us to reliably infer that the two bodies have the same temperature.

To this purpose we follow a bottom-up path, from (i) sensors as non-calibrated, and nevertheless useful, instruments to (ii) calibrated instruments, to (iii) the broader scenario in which the metrological traceability of measurement results is guaranteed by the dissemination of measurement standards (and therefore metrological traceability) and the definition of measurement units.

Sometimes pre-measurement is enough

Quality control and management are sometimes introduced as inherently connected to measurement: "if you can't measure it, you can't control it", or "you can't improve it", or "you can't manage it", is a commonly read and discussed motto. While data-driven and information-enabled decision making is, all other things remaining the same, usually better than decision making based on gut feeling or subjective experience only, that *ceteris paribus* condition should not be neglected. Indeed, measurement has costs that – though usually hidden in the black box that allows to use (2) instead of (1) – could be socially high, and therefore not necessarily justified. Let us consider two cases.

Suppose that we want to maintain the temperature of a system within a given range without the manual intervention of a human being. While the automatic feedback control system we are going to introduce must include a sensor of temperature, its operation could be of pre-measurement only. Indeed, we can be allowed to choose the set point by specifying not a value of temperature but a temperature as such. This is the case when the control command would be, for example, not “keep 20.0 °C” but “keep the current temperature”, whatever it is. In this case, the system could simply somehow record the sensor output – say, the voltage of a thermocouple – at the set point and later compare it with the sensor output produced during the system operation and trigger the actuator if the difference is greater than a given tolerance, in turn set as a perceived acceptable difference of temperature.

Let us take the second case from a completely different domain, by asking whether and under what conditions the grades given by a teacher to her students may be considered measurement results, instead of the teacher’s subjective opinions. When designing an evaluation test, her first step could be to prevent subjectivity by adopting explicitly stated evaluation criteria (e.g., establish the conditions that make each answer right or wrong, and count the number of right answers), but this would still lead to information on students’ competence in instrument/test-related values, and therefore to pre-measurement results. A possibly desirable improvement would be then to define a public scale for the competence under evaluation and then to connect it to the test outcomes (*n* right answers to this test correspond to the competence value *x*, etc.), thus making the evaluations of different teachers produced by different tests comparable with each other. However, this could be a challenging endeavor, particularly if the considered competence is very context-dependent or a widely agreed definition of it is still not available. In these situations, if the local comparability of test results is acceptable, pre-measurement is sufficient and much more easily and cheaply achievable.

It is only when pre-measurement is not enough, because the produced information is expected to be intersubjective, that the operation of well-behaved sensors – like good thermocouples and competence tests – is not sufficient, and the metrological system becomes a critical component of the process.

Instrument calibration

Let us consider again the simple case of an alcohol thermometer, and suppose for the moment that a scale of temperature has been somehow already defined and made public, so that everybody can in principle relate given temperatures to given values on the scale, thus agreeing for example which etched mark on the thermometer scale corresponds to the temperature of 20 °C, which corresponds to 21 °C, and so on. This is the first precondition for the thermometer to be operated as a measuring instrument, and not only to perform a pre-measurement as shown above. The second precondition is an operationalization of the first one: some of such (temperature, value of temperature) pairs must have been reliably realized in suitably chosen objects o_1, o_2, …, whose temperatures $T(o_1)$, $T(o_2)$, … are sufficiently stable and known in their values v_1, v_2, … on the given scale, i.e., $T(o_1) = v_1$, $T(o_2) = v_2$, … Objects with these features are called *measurement standards*, where the concept 'measurement standard' is in fact defined by the *International Vocabulary of Metrology* (VIM) as the "realization of the definition of a given quantity, with stated quantity value and associated measurement uncertainty, used as a reference" [6] (note that the correct phrase, "realization of the definition of a quantity", is often shortened as "realization of a quantity").

The process that transforms a temperature sensor into a measuring instrument is called *calibration*, and is functionally aimed at identifying how public values of temperature relate to local values of instrument positions, called "indications" in the VIM. In the ideal, and formally simplest, case, this relation is a {temperature values}→{position values} function. Again in the simplest case, such a *calibration function* is invertible – i.e., no two distinguishable temperature values are mapped to the same position value – and is the informational counterpart of the transduction function {temperatures T}→{positions p} realized by the instrument. This is why calibration can be intended as aimed at characterizing the transduction behavior of the sensor at the core of a measuring instrument [7].

If no hypotheses are made on the sensor behavior, the calibration function is built by making the instrument interact with some suitable "working" measurement standards, that in fact are "used routinely to calibrate or verify measuring instruments or measuring systems", according to the VIM definition [6]. The result of each interaction is a (value of the temperature realized by the standard, value of the position reached by the alcohol as the result of the interaction) pair, and the list of these pairs provides a partial extensional definition of the calibration function, that can be completed by means of suitable interpolations. An alternative, and more usual, strategy assumes that the transduction function has a known parametric analytical form, so that the calibration is aimed at estimating the values of the function parameters. For example, if the instrument behavior is supposed to be linear – i.e., its sensitivity defined as the derivative or the finite difference of the transduction function dp/dT or $\Delta p/\Delta T$ is constant – only two parameters have to be estimated, and therefore the interaction of the instrument with two measurement standards, each realizing a different temperature, is sufficient.

In fact, the description above is a simplification of what an instrument calibration is. The broader picture is given, once again, by the VIM definition of ‘calibration’: “operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication” [6]. The key point here is the acknowledgment that the instrument behavior is not perfectly repeatable, and then that a single temperature could be transduced to several different positions, and then that, conversely, one observed position could correspond to several different temperatures. Hence, in the more realistic case, the outcome of a calibration is not a function, but “the strip of the plane defined by the axis of the indication and the axis of measurement result, that represents the relation between an indication and a set of measured quantity values. A one-to-many relation is given, and the width of the strip for a given indication provides the instrumental measurement uncertainty.” [6].

Indeed, instrumental measurement uncertainty is a core component of the quality of the information produced by a measurement, but surely not the only one [3]. The measurement standards required to calibrate any measuring instrument are in turn non-ideal devices obtained by non-ideal processes, and these non-idealities affect the quality of measurement results with respect to their non-complete intersubjectivity. To the whole scenario of metrological systems we devote our attention now.

Metrological traceability: generating intersubjectivity by defining units and disseminating measurement standards

As already discussed, the fundamental condition of intersubjectivity for measurement results is to guarantee that the same measured value, as reported in different places and times and produced by means of different measuring instruments, corresponds to the same quantity, so that, for example, from

temperature of body *A* here and now = 23.4 C

and

temperature of body *B* there and then = 23.4 C one can reliably infer that

temperature of body *A* here and now = temperature of body *B* there and then (3)

(not dealing with measurement uncertainty for the sake of simplicity)

Were values of quantities, like 23.4 °C, purely mathematical entities, this inference would be a trivial consequence of the transitivity of the equality relation. But, as argued in [1], values of quantities are classifiers for quantities of objects, which are empirical entities, as highlighted by the reference to a unit, the degree Celsius in the example, in them. Hence, inference (3) is valid until the quantity stated to be the unit is actually the same everywhere and everytime, a condition that the VIM calls *metrological traceability*, the "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" [6]. In fact, as measuring instruments need to be calibrated by means of measurement standards, each standard is expected to realize a (quantity, value of a quantity) pair, for example (a given temperature, 20 °C). This is obtained by comparing the quantity realized by the standard with the quantity realized by another, already available, standard, so that, for example, from

temperature of standard *A* = 20 °C

and

temperature of standard *A* = temperature of standard *B*

one can reliably infer that

temperature of standard *B* = 20 °C

a process that is also called *calibration*, now performed on a measurement standard instead of on a measuring instrument.

The unbroken chain of calibrations mentioned in the definition above relies therefore on a principle of delegation: any measuring instrument is calibrated against one or more measurement standards, and a measurement standard is usually calibrated against another measurement standard, which is in a "higher" position in such a *traceability chain*, where the concept 'metrological traceability chain' is in fact defined by the VIM as a "sequence of measurement standards and calibrations that is used to relate a measurement result to a reference" [6]. The more a traceability chain for a given quantity is reliably widespread in the society, the more the measurement results produced by the instruments connected to that chain are traceable, and therefore able to convey intersubjective information: this justifies the importance of a both

technically and organizationally effective worldwide metrological system [8], as today grounded on the National Metrology Institutes (like NIST in the USA, PTB in Germany, NPL in UK, etc.) under the coordination of the International Bureau of Weights and Measures (BIMP) in the context of the Metre Convention. This is a critical component of the so-called *quality infrastructure*, of which metrology, together with standardization and accreditation, is a pillar [9].
At the root of the entire system there must be a *public scale* of the relevant quantity, where such a scale can be derived by somehow defining a unit for ratio quantities, or a unit and a zero for interval quantities, as it is the case of thermodynamic temperature (whose SI unit is the kelvin) and thermometric temperature (for example the Celsius scale, which is now defined in reference to the kelvin, and in the past had its zero defined in reference to the freezing point of water and its unit as one hundredth of the difference between the boiling and the freezing point of water) respectively [1]. Let us focus here on the simpler and more usual case of ratio quantities, for which a public scale is obtained by a unit with its multiples and submultiples. For a measured value, like 296.5 K, to be able to convey intersubjective information, the quantity that is the unit – the kelvin in the example – must then be known to be the same quantity everywhere and everytime.
If the concerned quantity is functionally dependent on other quantities whose unit has been already defined, such a functional dependence can be exploited to define the sought unit. An obvious case is about frequency, defined as duration to the minus one: once a unit of duration (the second, in the SI) has been defined, the unit of frequency is immediately defined as the unit of duration to the minus one (the hertz, in the SI) (and note that there is nothing intrinsic in the direction of this functional dependence, so that the argument could be reversed, by defining the second as hertz to the minus one). But of course this delegation process – defining a unit in reference to somehow previously defined units – requires a starting point. To this purpose, four strategies have been pursued in the course of history [5]: the case of length is particularly clear on this matter (see Fig.1).

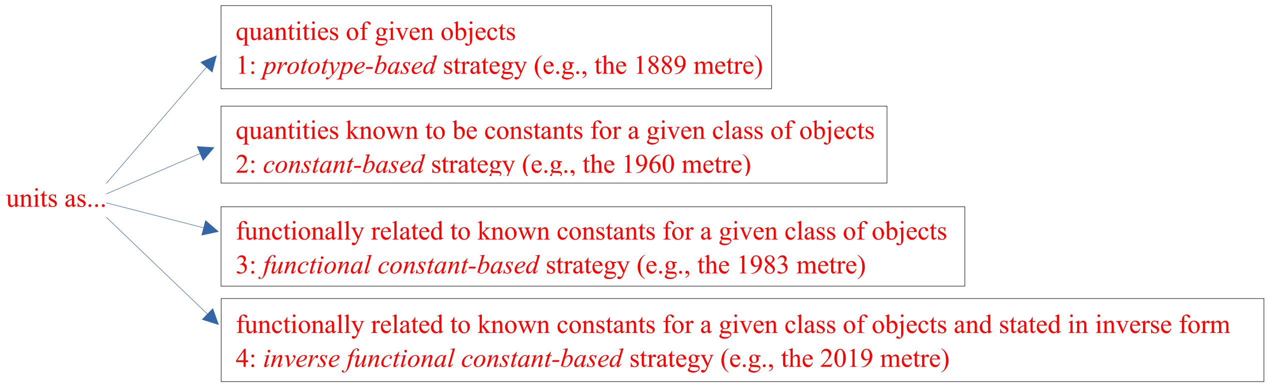

Fig.1. The four strategies pursued for defining units: the case of length.

First strategy: units as quantities of artifacts

The definition of a unit as the quantity of a given, suitably manufactured, object, sometimes called a "prototype" or an "artifact", is the first historically adopted strategy. In 1889 the first General Conference of Weights and Measures (CGPM) so defined the metre, stating that "the Prototype of the metre chosen by the CIPM (...) at the temperature of melting ice shall henceforth represent the metric unit of length" (this and the other definitions of the metre that follow are taken from the SI Brochure [10]), where the mentioned prototype was in fact a specially manufactured rod.

While conceptually simple, this strategy has at least two drawbacks, that have become more and more apparent with the progressive globalization of measurement science and its applications. First, objects at the anthropometric scale are usually not completely stable, with the consequence that, once a definition like

metre := length of a given prototype

is agreed, any change of the length of the prototype will result in the change of the numerical values of all the lengths measured in reference to that unit, even if the lengths as such did not change (this could have been the case of the kilogram, defined until recently as the mass of a given object, the International Prototype of the Kilogram: in 1994, a verification revealed that most copies of the Prototype appeared as if they had gained some mass, despite their independent handling and storage; plausibly, it was instead the Prototype that had lost mass [11]). Second, defining a unit as the quantity of a given object implies that all traceability chains must start from that object, and therefore that all measuring instruments for that quantity must be directly or indirectly calibrated against it: this is operationally inconvenient and could generate political struggles, given the power that the situation confers to the owner of the object.

Second strategy: units as constant quantities of classes of objects

With the aim of avoiding these problems, another strategy has been developed, based on the consideration that some domain-related theories may assert the existence of classes of objects that in given conditions have constant, and therefore stable, quantities. A unit can be then defined as one of such constants, or, were the constant too far from the anthropometric scale to be suitable for its expected use, as an appropriate multiple or submultiple of the constant. In 1960 the CGPM redefined the metre accordingly, as "the length equal to 1 650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the krypton 86 atom". The critical point of this definition is the assumption that the wavelength of the chosen radiation is constant, whereas the numerical value, 1 650 763.73, was only chosen to guarantee that the metre remained the same length despite the change of its definition.

With respect to the previous one, this strategy has an essential theoretical grounding, as its definition of the metre assumes the constancy of a quantity, as indeed implied by a theory.

Third strategy: units as constant quantities in a system of quantities

The previous two strategies assume that for each relevant general quantity, like length, mass, duration, and so on, a unit is independently defined. This is obviously possible, but also very ineffective, once it is acknowledged that physics provides us with a knowledge of the physical world in terms of a set of general quantities mutually connected in a network through relations that are either definitional or empirical, the latter being physical laws (thus justifying the term "nomological network", where the adjective comes from the Greek "nomos" meaning "law"). Such a network is what the VIM calls a *system of quantities*, the most important case being the International System of Quantities, as documented in the ISO and IEC 80000 series of technical standards.

By exploiting the relations in a system of quantities, a more sophisticated version of the previous strategy allows for the definition of a unit as a function of constant quantities of different kinds, and possibly of previously defined units. This is how in 1983 the CGPM redefined the metre, "the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second”, where, once again, the numerical value was chosen to guarantee that the metre remained the same length.

This strategy adds a structural context to the theoretical grounding of the second strategy, given that its definition of the metre assumes both the relation, length = speed times duration, and the constancy of the speed of all light beams in vacuum and of the quantity according to which the second is defined. It is then basing on this strategy that a system of units is an actual system and not only a list of quantities: for example, the SI includes some *base units* (the metre, the kilogram, the second, …), from which all remaining units (the newton, the joule, the watt, …) are functionally derived.

Fourth strategy: units as quantities fulfilling a numerical condition on constant quantities in a system of quantities

A straightforward next step of the structural and theoretical standpoint underlying the previous strategy could lead to defining a system of units by taking some quantities, chosen as constants according to the best available theories, setting the value of each of them to 1, and giving a name to them as the so-defined units. For example, the charge of the electron could be set to 1 el, the speed of light in vacuum to 1 li, Planck constant to 1 pl, and so on. Appropriate definitions would be then stated in inverse form: “the el is the unit of electric charge, defined by setting the numerical value of the charge of the electron to be 1 in the unit el”, “the li is the unit of speed, defined by setting the numerical value of the speed of light in vacuum to be 1 in the unit li”, and so on.

While effective for some physicists, who indeed already adopt units such as the electronvolt instead of the joule, this would be hardly acceptable by the society at large – and, of course, metrology is for the whole society, and not only top science – for at least two reasons, both related to the quantities to be chosen as defining constants. First, some of such constants are instances of general quantities that are unusual in daily life, like action in the case of Planck constant, and hard to understand without sufficient background knowledge in physics. Second, such constants are typically so small, like Planck constant, or so large, like the speed of light in vacuum, with respect to the anthropometric scale that values of quantities of daily life objects would be cumbersome to handle because numerically very large or very small.

However, these problems are not really critical, as the previous strategies already taught us how to solve them. In particular, the second problem can be easily solved by introducing some appropriate numerical factors, so that for example the unit of electric charge could be defined as "the coulomb is the unit of electric charge, defined by setting the numerical value of the charge of the electron to be $1.602\ 176\ 634 \times 10^{-19}$ in the unit C". Indeed, the 2019 CGPM definition of the metre follows this blueprint, and it is only more complex due to the fact that among the chosen defining constants there is a speed and a duration but not a length: "the metre (...) 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 $\Delta\nu_{Cs}$".
Interestingly, in a so-defined system of units, grounded on a system of quantities and a set of defining constants, the distinction between base units and derived units does not have any functional role anymore. Consider, for example, that, were "X" the name of the unit of speed and "x" its symbol, the definition of X would be almost identical to, and in fact simpler than, the one of the metre: "the X 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 x".
This developmental path, where a unit is defined as

1. the quantity of a given object (*prototype-based* definition, as in the 1889 definition of the metre), then
2. the quantity considered to be constant for a class of objects (*constant-based* definition, as in the 1960 definition of the metre), then
3. a quantity functionally related to the quantities considered to be constant for some given classes of objects (*functional constant-based* definition, as in the 1983 definition of the metre), then
4. a quantity functionally related to the quantities considered to be constant for some given classes of objects through some numerical factors and stated in inverse form (*inverse functional constant-based* definition, as in the 2019 definition of the metre),

may be interpreted as a blueprint of the options towards the structural guarantee of better and better intersubjective information that a metrological system can provide to the society.

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POSSIBLE HIGHLIGHTS

- ***Pre-measurement*** conveys information that is correctly interpretable only when it is referred to a given instrument and under the condition of instrument stability.
- ***Calibration*** transforms a sensor into a measuring instrument
- ***Intersubjectivity*** of measurement results is ensured by calibration and metrological traceability

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