MEASUREMENT SCIENCE AND ITS EVOLUTION

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Contents

1. The role of measurement in science, technology, society
2. Basics of measurement science
2.1. The structure of measurement process
2.1.1. Measurement as direct reference comparison
2.1.2. Measurement as indirect reference comparison
2.2. Transducer calibration
2.3. Objectivity and inter-subjectivity in measurement
2.3.1. Measuring systems as tools for objectivity: performance indicators
2.3.2. Calibrated references as tools for inter-subjectivity: the metrological system
2.4. The qualification of measurement processes
2.5. Open issues
3. The past and the present of measurement science
3.1. The historical roots of the concept of measurement
3.2. What does quantification have to do with measurement?
3.2.1. Systems of quantities and systems of units
3.2.2. Quantities and measurability
3.2.3. Quantities and properties
3.2.4. Representational theories of measurement and the scope of measurement
3.2.5. Physical vs. non-physical measurement: a note
3.3. How can the quality of measurement results be evaluated?
3.3.1. On the concept of true value of a quantity
3.3.2. Dealing with measurement uncertainty
3.3.3. Measurement uncertainty as a decision making tool
4. Some current trends
Acknowledgments
Glossary
Bibliography
Biographical Sketch

Summary

Measurement is a basic process allowing us to acquire and represent objective and inter-subjective information on properties of (both physical and non-physical) systems. After an introduction on the role of measurement in science, technology, society (Section 1), the measurement process is presented as an experimental comparison with a reference whose result is represented in terms of property values. The role of measuring systems to guarantee objectivity and of the metrological system, allowing the calibration of

measuring systems to appropriate standards, to guarantee inter-subjectivity is analyzed, and some related performance indicators are presented (Section 2). Two fundamental issues are then discussed, also with some references to the complex history of measurement (Section 3): first, what does quantification have to do with measurement?, leading to examine the relation between properties and quantities, the concepts of systems of quantities and of units, the concept of evaluation and property type, and their formalization in the context of representational theories of measurement; second, how can the quality of measurement results be evaluated?, leading to compare the traditional concepts of true value and measurement error with the current standpoint that emphasizes the concept of measurement uncertainty, and justifying the position that measurement results can be represented as sets of property values or, even more generally, probability distributions of such values. The synthetic review of some current trends of measurement science and technology (Section 4) concludes the work.

1. The Role of Measurement in Science, Technology, Society

Human beings have been performing measurements for many centuries and in many different contexts. By means of measurement scientists acquire mathematically processable information on phenomena, with the purpose of both supporting the formulation of theories and experimentally validating them, but measurement has a critical role also for technology and society, where it was first exploited to support relational activities such as trade. This original function is even more relevant in today's global economy that relies on measurements whose results might be accepted and interpreted with the same meaning worldwide. The document "Evolving needs for metrology in trade, industry and society and the role of the BIPM" [BIPM 2007] states that currently "an estimated 80 % [of the world trade] is affected by standards and regulations" and that according to various studies "the cost to producers and service providers of complying with "standards" can be 10 % of production costs". Of course, measurement is the basis to assess such compliance. The document lists some of the application areas where the role of measurement is increasingly critical: they include "transport; information technology, navigation and telecommunications; electronics and optics; electromagnetic and ionizing radiation; energy; climate change, environmental and pollution control; clinical chemistry and laboratory medicine; food safety; anti-doping; pharmaceuticals; forensics and security".

Measurement also has a critical role in ensuring public trust in official and commercial transactions, in labor environments, health and safety and in assessing conformity with regulations, e.g., in aviation and environmental and pollution control (see the introductory presentation in Metrology – in short, 3rd edition, 2008 [MIS 2008]). This is specifically the task of legal metrology (www.oiml.org) and accreditation (www.ilac.org) bodies. As an example, the Directive 2004/22/EC of the European Parliament and of the Council of 31 March 2004 on measuring instruments (commonly known as the "MID") [MID 2004] gives legal specifications for: water meters; gas meters; active electrical energy meters; heat meters; measuring systems for continuous and dynamic measurement of quantities of liquids other than water; automatic weighing instruments; taximeters; material measures; dimensional measuring instruments; exhaust gas analyzers.

These listings might be sufficient to justify the claim: measurement is pervasively exploited in many human activities.

The mentioned distinction between the scientific, industrial, and social applications of measurement is in fact elusive, and their intersection is open to cross-fertilization. While in some specific scientific endeavors measurement can be a goal in itself (e.g., the classical experiments performed by R. Millikan to determine the elementary electrical charge), obtaining measurement results is generally instrumental to data processing and particularly decision making.

The black box model provides the basic representation:

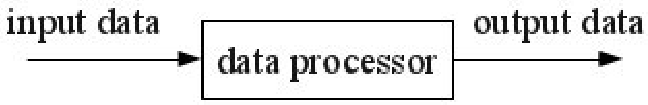

Figure 1. black box model of data processing.

(a trivial example: the price of a given amount of an entity depends on the unit price and the amount, the inputs to be processed to obtain the required output). While it is implied by this model that the outputs depend on the inputs, less obvious is the fact that the *quality* of outputs (interpreted as accuracy, precision, reliability, …) is conditioned by the quality of the inputs. This can be expressed by the so-called GIGO (garbage in, garbage out) principle: as data processing cannot increase the quality of processed data, low quality input data will lead to low quality output data. Measurement is thought of here as a tool (or even: the tool) to experimentally acquire data whose quality is high enough for the given processing purposes:

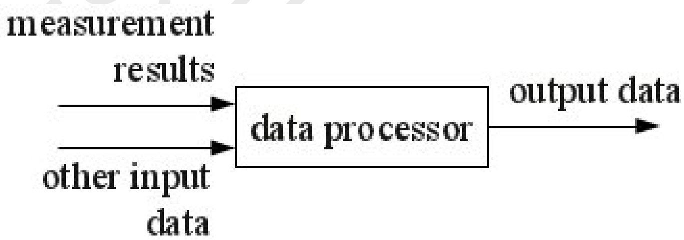

Figure 2. black box model of measurement-based data processing.

In a common situation of measurement-supported decision making, the current state of the entity under consideration, as known by measurement (entities of diverse nature may be involved, not only physical objects but also phenomena, processes, events, …: we will generically denote them as *systems under measurement*), is compared with a nominal state, typically chosen by design, and a decision has to be made on the basis of the result of the comparison, for example in terms of conformity of the measured state to the nominal one. A specialized version of the previous diagram applies in this case:

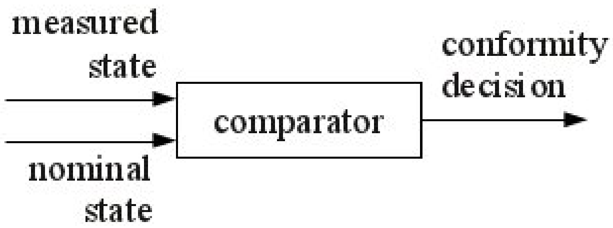

Figure 3. black box model of measurement-based conformity decision.

This highlights the basic *pragmatics of measurement*: its results are aimed at being able to effectively support processing and decision. As a consequence, they are required to fulfill a general trade-off between minimal quality (to convey useful information) and maximal cost (to be affordable in the given context). For example, if the decision is on the conformity of an industrial product to a specification requiring the nominal length to have a tolerance, i.e., admissible variation, of the order of magnitude of 10^{-4} m, then any measurements leading to results with an uncertainty of 10^{-3} m or more will be useless, and any measurements leading to results with an uncertainty of 10^{-5} m or less will be plausibly uselessly costly, for the decision. Under the simplification that quality and cost are linearly related, the structure of the decision space can be then depicted as follows:

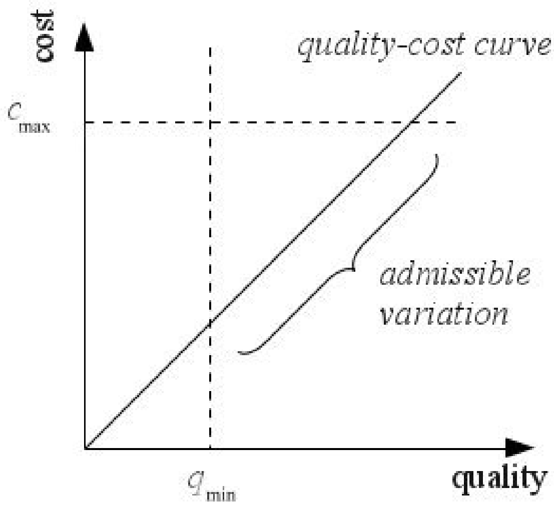

Figure 4. simplified version of the quality vs. cost trade-off of measurement.

On the other hand, this functional structure applies not only to measurement: the data to be processed may be obtained by other processes of information (acquisition and) representation, such as guess or judgment by experience. Hence the fundamental issue arises: *how is the customary claim justified that measurement is able to convey information with a quality that, e.g., guess cannot guarantee?*

While a more detailed answer will require us to analyze the structure of a measurement process, and possibly to distinguish between different domains of applications, the basic conditions that measurement is expected to fulfill can be given independently of any technical analysis. Measurement results are customarily considered to convey information:

- that is related to the system under measurement and is independent of the surrounding environment, that typically includes both the measuring system and the subject that is measuring: this is a requirement of *objectivity*;
- that is interpreted in the same way by different subjects in different places and times: this is a requirement of *inter-subjectivity*.

Of course, these conditions do not generally hold in the case of data obtained by processes such as guess or judgment by experience. Hence, the previous question can be specified as: *how is the objectivity and the inter-subjectivity of results guaranteed in measurement?*

These conditions of objectivity and inter-subjectivity critically apply to the measurement of both physical (length, mass, power, …) and non-physical properties, such as attitude and happiness, whose measurability is sometimes still an open issue, deeply tied in the theoretical background of their scientific domain.

Measurement science, sometimes also called "metrology", is the organized body of knowledge devoted to designing measuring systems and characterizing their performance in compliance with these principles and conditions. On the other hand, if the conceptual frameworks about measurement in, e.g., quantum mechanics and psychology are compared with each other, slight commonalities could be found. This highlights the potential usefulness of identifying a set of concepts and related terms that can be shared among all researchers and practitioners involved in measurement, as independently of any specific field as it is appropriate. Not only would the mutual understanding be increased, but also, and even more critically, the obtained results and techniques might be transferred, the lessons learned, the mistakes avoided.

Noteworthy from this viewpoint are the activities of the Joint Committee for Guides in Metrology (JCGM), started in 1997 and currently performed by eight prominent organizations:

- International Bureau of Weights and Measures (BIPM, www.bipm.org);
- International Electrotechnical Commission (IEC, www.iec.ch);
- International Federation of Clinical Chemistry and Laboratory Medicine (IFCC, www.ifcc.org);
- International Laboratory Accreditation Cooperation (ILAC, www.ilac.org);
- International Organization for Standardization (ISO, www.iso.org);
- International Union of Pure and Applied Chemistry (IUPAC, www.iupac.org);
- International Union of Pure and Applied Physics (IUPAP, www.iupap.org);
- International Organization of Legal Metrology (OIML, www.oiml.org).

The JCGM (http://www.bipm.org/en/committees/jc/jcgm) is promoting a shared knowledge on fundamentals of measurement science through two reference documents:

- *International vocabulary of metrology – Basic and general concepts and associated terms* (VIM, http://www.bipm.org/en/publications/guides/vim.html) [VIM3 2008];

- *Evaluation of measurement data – Guide to the expression of uncertainty in measurement* (GUM, http://www.bipm.org/en/publications/guides/gum.html) [GUM 2008], and its supplements.

Although still in evolving state and mainly focused on the measurement of physical quantities, these documents can be acknowledged as an up-to-date synthesis on the basic understanding about measurement science. As such, they will be taken as backgrounders for the present work, with some generalizations to maintain the discourse as comprehensive as possible.

2. Basics of measurement science

According to a black box model, measurement may be interpreted as a process producing an information entity, called the *measurement result*, that is supposed to convey information on the *system under measurement*:

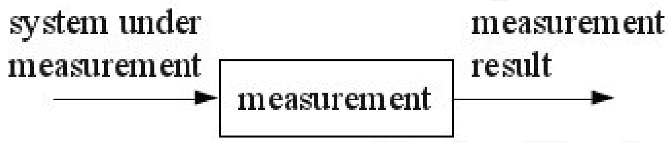

Figure 5. black box model of measurement.

This characterization is very generic, and requires some specifications.

- The actual object of measurement is not the system under measurement, for which the term “measured system” is indeed misleading, but an *individual property* of such system (such as the length of this table, the color of this paper, the loudness of this sound, the intelligence of this person). The individual property intended to be measured is called the *measurand*.
- A measurement result conveys information on the measurand in the form of *property values*, in this case called *measured property values*. Hence, measurement can be operatively thought of as a process aimed at the representation of the measurand by means of property values. *General properties* (such as length, color, loudness, intelligence) are then the theoretical counterpart of such process: any general property can be modeled as a function that, when applied to an individual (such as this table, this sound, this person), is instanced into an individual property, that in its turn is represented by property values. The customary notation, e.g.:
  length(this table) = 1.23 m can be then interpreted as:
  general property(*system under measurement*) is *individual property*
  and:
  individual property is represented by *property value*
  (unfortunately there is not a single standard terminology as for the distinction general vs. individual property, that for example is sometimes rephrased as property vs. manifestation of property).
- The distinction between individual properties and property values is delicate but important for an appropriate characterization of the basics of measurement science: before measurement the individual property is known for its being related

to a given system (this length is of this table) but the value by which it can be represented is unknown. In a complementary way, property values are given but still unrelated to the individual property. Measurement is aimed at identifying an appropriate association between the individual property and a property value. For a given system s and a general property p, to maintain this distinction explicit the individual property will be denoted as $p(s)$ and a related property value as v, so that the fact that a measurement leads to assign a property value to an individual property can be written as:

$p(s) = v$

On this basis the following notation may be adopted:

$s_1 \approx p s_2$ or equivalently $p(s_1) \approx p(s_2)$: the systems s_1 and s_2 are indistinguishable with respect to the general property p, or equivalently the individual properties $p(s_1)$ and $p(s_2)$ are indistinguishable (e.g., these two tables have the same length);

$v_1 = v_2$: the property values v_1 and v_2 are equal (e.g., as in the case 2.34 m = 234 cm).

- The result of only simple and rough measurements is a single measured property value. In general, whenever their uncertainty has to be taken into account, measurement results are more complex entities, such as intervals of property values or probability distributions defined on the set of the property values. In the following (see Section 3.3) we will further discuss the subject of uncertainty in measurement, by which the quality of its results can be formalized.
- Measurement results are sometimes referred to *quantities* instead of properties. On the basis of the assumption that quantities are properties but not all properties are quantities, in the following (see Section 3.2) we will discuss the meaning and the reasons of this specification. Moreover, philosophy of science is used to distinguish between properties and relations, where properties apply to individual entities and relations to couples, triples, ... of entities (for example, diameter is a property and distance a relation). On the other hand, the concept of system under measurement has been left unspecified here, and therefore a couple, a triple, ... of entities may be assumed as a single system under measurement: hence, properties will be enough for the present work.

These entities – measurement as a process, systems under measurement, general and individual properties (and measurands in particular), property values – constitute the operative ontology on which measurement science is grounded (a task for a fundamental ontology would be to reduce this multiplicity by showing that some of these entities can be derived from the other ones, but this is a goal outside measurement science and therefore well beyond the scope of the present work).

A key issue arises here on the very concept of measurand, i.e., the object of measurement. Let us compare:

- the measurand is the quantity intended to be measured, i.e., the quantity to be measured;
- the measurand is the quantity subject to measurement, i.e., the measured quantity

(it might be noted that these definitions are those given in the current edition of the VIM [VIM3 2008] and in the previous one [VIM2 1993] respectively).

The point is that there can be (and in general there is) a difference between the property intended to be measured and the property that is actually measured. For example, one could be interested in measuring the length of an object at a given temperature, but at the moment of the measurement the temperature could be different from the specified one, or the measurement itself could modify the system with respect to its length, with the consequence that the result of the measurement would be referred to the wrong property. Or one would like to measure the intelligence of a person by means of a test, while actually obtaining only information on the ability of the person to be successful in that test, instead of on her intelligence.

The dilemma is grounded on the nature of measurement, that aims at representing an entity known *by identification*, the measurand (e.g., the length of this table), by means of an entity known *by description*, the property value (e.g., 1.23 m). This synthesis is the basic reason why measurement results are useful and, at the same time, why measurement is not a purely empirical process. It is the issue that in social sciences is customarily called of *construct validity*: is the measuring system actually measuring what it purports to measure?
By assuming:

measurand = quantity actually subject to measurement

as suggested in particular by operationalism [Bridgman 1927], the problem seems to be removed. But any radical operationalist point of view (e.g., Q: what is intelligence? A: it is the property measured by the IQ test) fails because measurement results are assumed to convey information on properties that are aimed at being used in relational structures, paradigmatically physical laws, that are known by theory and description, not identification. For example, in exploiting $F = ma$ to compute the acceleration a generated by a force F on a body of mass m, it is expected that the values substituted to F and m represent a force and a mass respectively, not something such as “the quantity measured by this instrument” and “the quantity measured by that instrument” only.

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Biographical Sketch

Luca Mari received the Laurea degree in physics from the University of Milano, Italy, in 1987 and the Ph.D. degree in measurement science from Politecnico di Torino, Italy, in 1994. He is currently with Università Carlo Cattaneo – LIUC, Castellanza, Italy, where he is a full professor of measurement science and teaches courses in measurement science and system theory, that are also subjects of his research interests. Prof. Mari is currently Chairman of Technical Committee 7 – Measurement Science – of the International Measurement Confederation (IMEKO) and International Electrotechnical Commission (IEC) expert in the Joint Committee for Guides in Metrology (JCGM) – Working Group 2, on the International vocabulary of metrology (VIM).