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A new definition of measurement

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Abstract

Existing definitions of measurement presented by many scholars in metrology are presented and reviewed. A brief synopsis of advances in thinking about the nature of measurement is also presented. A new definition of measurement is proposed: "Measurement is an empirical process, using an instrument, effecting a rigorous and objective mapping of an observable into a category in a model of the observable that meaningfully distinguishes the manifestation from other possible and distinguishable manifestations". This definition is discussed in the light of the more recent developments in the conceptualization of measurement.

1. Introduction

Various measurement theorists have proposed definitions of measurement. The problem confronting all attempts at definition of measurement is to be, at once, both general enough to include every kind of representation of observables that could reasonably be regarded as measurement whilst excluding cases that are too vague or otherwise should not be regarded as measurement.

This paper will review some definitions of measurement and will propose a new definition, with an argument supporting the adoption of the new definition.

2. Definitions of measurement

The prevailing modern view of measurement is traceable to Galileo. Measurement became important in the Renaissance because science shifted from Aristotelian a priori discourse to an empirical basis [1]. Galileo's dictum, reflecting this shift to empiricism, is: "Count what is countable, measure what is measurable and what is not measurable, make measurable" [2]. A naive interpretation finds Galileo sought to quantify everything but ignores that Galileo was a rhetor speaking at the start of empirical and quantitative science [3]. That Galileo was a rhetor is important because he was preaching with the goal of persuading others to enter his, renaissance, vision of empirical, as opposed to Aristotelian, learning. Kelvin repeated the essence of Galileo's dictum in 1883:

> I often say that when you can measure what you are speaking about, and express it in numbers you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind: it may be the beginning of knowledge, but you have scarcely advanced to the stage of science whatever the matter may be [2].

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The interpretation of this over cited quotation is debatable. The effectiveness of quantification in many endeavors has spawned the belief that measurement produces certainty and that quantification is essential to science [4]. Kelvin uttered the dictum in a rhetorical context where vigorous expression was useful to convey the benefit of quantification. But today "our culture invests a quality of real truth in numbers, analogous to the way in which [some] other cultures believe in the magical powers of names" [5] that Kelvin's dictum is eisegeted, in violation of the context of Kelvin's utterance, to produce an excessive interest and trust in quantification. Feinstein criticized the extreme of the popular eisegesis of Kelvin's dictum:

> One outdated paradigmatic concept—an extension of beliefs stated by Lord Kelvin—is the idea that scientific data must be expressed objectively in the form of dimensional measurements. This concept provided major enlightenment when it first became accepted as a paradigm; it has now led to major intellectual crises that remain unsolved by various ad hoc modifications of the basic paradigm, and is now being used to substitute for enlightened thought or to thwart it [6].

One popular definition sees measurement as:

> the quantitative determination of a physical magnitude by comparison with a fixed magnitude adopted as the standard, or by means of a calibrated instrument. The result of measurement is thus a numerical value expressing the ratio between the magnitude under examination and a standard magnitude regarded as a unit [7].

This definition relies on a comparison conception of measurement that asserts that two objects are equal, or at least indistinguishable, with respect to the observed characteristic when examination fails to reveal difference. Measurement, then, is a negative process of failing to reveal difference rather than a positive process of demonstrating equality or equivalence. This comparison view of measurement builds on Campbell's definition:

> Measurement is the process of assigning numbers to represent qualities: the object of measurement is to enable the powerful weapon of mathematical analysis to be applied to the subject matter of science [8].

Campbell's definition obviously constructs on the view expressed in Kelvin's dictum of four decades earlier. Hofmann contrasts this with a broader sense of measurement:

> Measuring in a narrow sense (measurement) is the experimental comparison of a measured quantity with a metrological standard. Measuring in a wide sense (classification) is the experimental comparison of a measured object with a particular standard (pattern) [9].

Hofmann's wider sense suggests recognition that measuring device output is information about the state of the observed in its environment [10].

Ellis begins his 1960 paper on measurement defining it as:

> the means by which mathematics is applied to the study of physical phenomena [11].

This definition is somewhat ambiguous, seeming to support the simple numeration understanding of measurement, since the popular notion of mathematics as pertaining to numeration and arithmetic operations. However, Ellis' definition is not necessarily so limited because mathematics includes branches concerning the properties of symbolic and discrete representations of things. Later Ellis did not aim to establish a tighter definition of measurement, but rather to continue the same theme with: "All measurement involves the application of arithmetic", [12, p. 4] as the commencement point for his exploration of measurement. This lack of a tight definition enabled Ellis to explore measurement without the limitations imposed by a rigorous definition. Consequently [12] is a work developing the concepts associated with distinguishability of manifestations and the structure and properties of scales, using the work of Stevens [14], and the properties of the manifestations that form the basis of measurement.

Ellis' definition emphasizes on aspect of Campbell's definition, above.

Piotrowski defines measurement as "quantitative observation" [13] following the other aspect of Campbell's definition [8], and limits all discussion to situations in which the purpose is quantitative output. Piotrowski presents a theory with two domains, the real object domain and the representative abstraction domain and measurement is the process of transformation from the real to the abstraction. Thus, measurement is the process of mapping reality to a model representing it in the abstract, but quantitative domain.

Stevens asserts that measurement effects a kind of isomorphism of the observed and the numbers used to describe it in the measure domain [14], and that the kind of representation scale depends on the empirical operations which may be performed on the observed. He presented a table of scale types; Nominal, Ordinal, Interval and Ratio, and the fundamental mathematical characteristics and formulae defining the structure of the mapping space of each type [14]. This led him to define measurement as a set of consistent rules for assigning numbers to things [14]. The idea of a "set of consistent rules to assign numbers to things" is not quite general enough, since it appears to overlook the matter of assigning labels to categories. After Stevens, the other definitions cited have followed two families, with all but Piotrowski recognizing the breadth of kind of scales that may be used to represent states of nature. Piotrowski, unusually in the formal measurement theory literature limits his definition to the narrower sense referred to by Hofmann, but in this is consistent with the majority of work in introductory texts on practical measurement.

Finkelstein variously defines measurement, first:

Measurement is "an empirical operational procedure which assigns numbers to members of a class of entities, in such a way as to describe them; by which is meant that relations between these numbers correspond to empirical relations between the entities to which they are assigned" [15].

This definition implies either that measurement can only obtain what Campbell [8] describes as quantities if the numbers assigned to things are the group of real numbers where the algebraic relation of the measures corresponds to the empirical relations of that to which they are assigned or demands some elaboration to state that the numbers into which the mapping is done must be understood as being members of a group with operations corresponding to the operations meaningful in the observed space. Finkelstein elsewhere defines:

> Measurement is the process of assignment of numbers to members of a class of attributes or characteristics of objects of the real world in such a way as to describe them. The assignment is an operational procedure so framed that the number assigned to an element describes it, that is, the relations between numbers assigned to different elements of the class, correspond to empirical relations between elements to which they are assigned [16].

This definition releases the limitation of the preceding definition by Finkelstein, that the numbers in the mapping domain may be misunderstood inappropriately narrowly.

> Measurement is an operation which objectively assigns numbers to quality manifestations of objects in such a way as to describe the manifestations [17].

The strength of this definition is that it emphasizes the objectivity of the measurement mapping process.

> Measurement is the process of empirical, objective assignment of numbers to the properties of objects and events of the real world in such a way as to describe them [2].

This definition makes explicit that measurement is an empirical, rather than an a priori process.

> Measurement, the objective representation of our empirical knowledge of the world by numbers, is an essential element of all science [18].

> Measurement is the assignment of numbers or other symbols by an objective, empirical process to attributes of objects or events of the real world in such a way as to describe them [19].

These definitions are all variations on the theme that measurement leads to description of objects through assignment of numbers, or possibly symbols, to manifestations of real things, thus describing the manifestations. The notion of the numbers being measures of things and describing manifestation of things asserts that the relation of the numbers and the manifestations are mutually implied [20]. Whilst part of the variation of definition is merely rhetorico-contextual Finkelstein's definitions reveal progress from emphasis on the quantitative to emphasis on the information gathering character of measurement and thus the insight into the manifestation conveyed by the measure. This growth of concept indicates a broadening of the concept of measurement to include more kinds of action as candidates for the title of 'measurement', and indicates a growth of interest in the descriptive power effected by measurement, as distinct from the process of obtaining a quantity of something in relation to the observed.

Three major works [21–23] in measurement theory do not provide formal definitions of measurement, either as their starting point nor as their conclusion. However, each develops the formal analysis of measurement in the post-Stevens [14] frame of the representational theory of measurement, investigating the formal, necessary and accidental properties of the relation of manifestations to their measures. This development implies an understanding of measurement consistent with the broader sense definitions, above, such as those of Finkelstein, rather than the narrower sense definitions of the other branch of thought.

3. Development of measurement theory

Measurement presupposes something to be measured and a theory which permits of a measure and a process for measurement [15]. The central problem of measurement is the theory, which permits development of a correspondence between the measures and the conceptual structure of the class of measurands as they exist in the real observed [15]. The theory is 'representational' in that the symbols assigned by measurement "must represent the perceived relations between the attributes of objects for that assignment to constitute measurement" [24]. Such a theory requires:

1. An empirical relational system corresponding to a quality;
2. A number relational system;
3. A representation condition;
4. A uniqueness condition [2, p. 8].

A process of comparing the manifestation of a property in two objects; the observed and the bearer of the standard, is used to perform measurement. In some cases there is direct comparison of the observed manifestation and the standard, and in other cases the comparison is indirect, using calibrated sensors. To go further and say that measurement is a comparison to find "the ratio of the magnitude of the property to a standard magnitude taken as unity" [2, p. 6] is too demanding because many properties cannot be compared so as to produce such a ratio.

The representation condition requires homomorphism of the observed and representation domains. Measurement is a homomorphism because it is not strictly one-to-one, but rather maps separate, but indistinguishable states to the same representation [2]. The uniqueness condition requires that the mapping from object to representation must be unique up to a specified transformation, and that transformation not alter the characteristics of the representation domain [2].

The first requirement for a measurement scale is establishment of a clear definition of the entity to be measured [2]. Scale establishment requires the concept of a class of manifestation [17]. Many variables of importance do not have satisfactory scales and prompt a search for new scales which are appropriate and effective for their description [20]. The process of developing a scale for a manifestation is a complex process of empirical investigation of the form of the manifestation, to determine the appropriate scale form required.

Finkelstein defines information in the context of measurement and compares this definition with that of Information theory concluding that in both cases "information is knowledge about an entity provided by an image of the entity under a mapping" [16]. Finkelstein and Watts [25] considered sensors as information machines transforming input to output by a one-to-one correspondence relation.

Finkelstein explained the purpose of instruments as:

> the acquisition of information by sensing and perception, the processing of that information and its final presentation to a human observer, or to other information processing machines [26].

This expression of the purpose of instruments reflects a shift of emphasis from assignation of numbers to manifestations [15] to the information extraction role of sensing implied in [25]. Finkelstein [16] argues that restricting measurement theory to numerical representation is too restrictive, and that symbolic representation is more general. Measurement has two objectives, the concise and the precise description of members of a class of objects. These purposes may be best effected through numerical or symbolic representation, depending on the case.

The weakest step in the measurement process is the decision of what to measure, and consequently the relation of the data to the required knowledge [27]. One may say the essentials of measurement system design involve answering:

1. What knowledge is sought?
2. What measurands need be used?
3. What must be the performance specification of the measurands?
4. How are the resultant measured data to be used? [27]

Sydenham's work is significant in that it was a beginning part of a new trend in the conceptualization of measurement and the purpose of measurement. The new trend places the act of measurement into the broader context of elicitation of information about the phenomena observed, and making that information meaningful and usable, rather than only describing the narrow act of measurement in and of itself. This contrasts with the earlier work of Finkelstein and Watts [25] in which the emphasis was on the information content of the measure data obtained by instruments, rather than Sydenham's emphasis on the perception of the observed gained by means of the measurement.

In the stream of thought started by Sydenham, Fiok and coworkers [28] criticized current measurement technique as being mainly indirect, and based on computer signal processing and calculation. The measurement technique that Fiok et al. identified and criticized is a consequence of conceiving of measurement in the older, narrower way as the act of applying instruments, reading measures, applying analysis and obtaining results. Fiok et al. [28] continued their discussion considering the relation of object, object model, and quantity, saying:

> The concept of quantity is and will remain one of the primary concepts in metrology and in mathematical modeling of physical objects. We propose only to broaden and generalize this basic concept. Our approach takes into account that:
>
> 1. Generally, quantity itself is not a property of real objects, it only models its particular property within bounds of the assumed mathematical model of the object;
>
> 2. Temporal and/or space aspects of object properties can be of major importance;
>
> 3. It is necessary to distinguish clearly different concepts named with the same term 'quantity' [28].

This quotation introduces the idea that quantities are the values which fit into mathematical models of the object, whatever mathematical form the values and the model take [28]. This is important in the development of a revised view of measurement because:

> Traditionally measurement has been treated as an experimental determination of the value of a physical quantity. Quantities were treated as real objects of measurement, but in fact they have a rather abstract and idealized character. Quantities are defined as the features of idealized objects or idealized phenomena, different from real ones. Everyday practice shows that no measurement can be separated from a part of objective reality: a physical object, called the measured object, whose chosen properties are to be quantitatively determined in effect of the measurement [29].

Fiok et al. developed an object oriented concept of measurement in which measurement involves finding parameters that fit into a particular model of the observed object by means of the application of instruments that determine the parameters empirically. Thus:

> In a general sense, the measurement process is aimed at setting up an image of the measured object. The image is mapping properties of the object and relations between those properties... The starting point of any measurement is selecting the structure of the model of measured object i.e. quantities describing the object and the forms of relations between them. Those relations are usually characterized by some equations with unknown values of parameters. The structure of the model describes the whole class of similar objects. The model of a particular object merges if the parameters assume particular values. So in effect of the measurement we in a general sense obtain values of parameters of the chosen structure which individualize the model ascribing it to a particular object [29].

So measurement is:

"an experiment of parameter identification of [the] mathematical model of the object to be measured" [29]. As a corollary, measurement may lead to whatever is required as a parameter in the mathematical model, so the output of a measurement process may be for example real numbers, or complex numbers, or series of real and complex numbers, or real or complex functions, or parameters of functions.

At the same time as Fiok et al., Sacerdoti et al. [30] presented a radical view of measurement:

> Measurement processes are the means by which man dialogues with the external world in order to enrich his knowledge. The processes pass through dialectic counter-reacted phases i.e.,

1. 'Historical phase', during which the 'receiver' learns to recognize forms and situations;
2. Organization of the experimental situations on the basis of the results;
3. Representation of the results.

This view of measurement sees knowledge advance as the result of an Hegelian process in which data gains significance through the dialectic of data and hypothesis being forced together to produce the synthesis of a new hypothesis until the matter settles on the new knowledge. The conception of measurement as part of an Hegelian process is radical because prior to this work measurement had always been regarded as part of a positivist approach to obtaining empirical knowledge.

4. Object oriented model of measurement

Ferris [31] presented an object oriented model of measurement, OOMM, to describe measurement scenarios. The OOMM contains the following elements:

1. A reality about which information is desired.
2. A collection of concepts about the class of which the reality is an instance.
3. A collection of processes and apparatus for measurement pursuant to 2.
4. A scale with which to express the measured results.

5. A set of possible data values which could result from measurement of each attribute.
6. A set of transformations for acting upon the data for the purpose of conclusion generation.
7. A set of possible conclusions concerning the reality.

Any measurement process is capable of identifying where, within the space permitted by the concept of the class the instance belongs, but is incapable of determining that the observed reality is not an instance of the class to which it is purported to belong. When measurement is understood in the frame of the OOMM 'measurement' must be redefined to recognize the issues embodied in the idea of the OOMM.

5. New definition

Measurement is an empirical process, using an instrument, effecting a rigorous and objective mapping of an observable into a category in a model of the observable that meaningfully distinguishes the manifestation from other possible and distinguishable manifestations.

6. Discussion

This definition of measurement differs from the majority of definitions discussed earlier in that it considers measurement from the perspective of the descriptive power of measurement in relation to the matter observed, emphasizing in particular that measurement results locate the observed in relation to the observer's understanding of the observed. This contrasts with the majority of the above definitions of measurement that regard measurement in a narrower way as the instrumented mapping of a reality onto a scale.

Measurement is an empirical process performed using an instrument. Thus some particular formal method and possibly, but not necessarily, equipment is used to perform the mapping from the reality of a state of nature to the measure. This means that the reality is observed using the means of the instrument in order to perform the mapping from the state of nature to the measure. To people from disciplines using physical measurement 'instrument' connotes hardware that interacts with the manifestation to produce an output from the hardware, the measure. In other disciplines, such as education or economics, that which is called an 'instrument' refers to a systematic means to perform the observations of the measurement process.

The inclusion of 'rigorous and objective' emphasizes that the process of measurement must be independent of any and all factors associated with opinion or subjectivity, and so measurement should be repeatable by any observer using the same instrument to perform the mapping in the same circumstances, or would have yielded the same results independent of observer in the particular case. Any process, the output of which depends on the person who performs the process is not objective, since the outcome is dependent on the active subject. Any process, the output of which varies, even though all other conditions remain constant, is not rigorous. Any process that is not rigorous or is not objective has output that mixes effects of the manifestation it is observing and other things, and so does not reliably inform the user of that manifestation that is claimed to be the subject of the process.

The outcome of measurement is a description of the observed as belonging within a category in the model assumed in the scenario. The model of the measurement scenario itself defines the meaningfully distinguished cases, the categories, into which the measurement mapping must place the observed. The categories in the model of the measurement scenario are such as to distinguish all cases that are functionally distinct, but at the same time, to aggregate all cases that are functionally indistinguishable. The result is that measurement performs a homomorphism, because the meaningful distinctions in the nature of the observed and the meaningful distinctions in the measure domain correspond, but there may be smaller variations in the state of nature that are not detected and mapped.

The new definition is distinct from that of Fiok et al. [29] in that Fiok et al. define measurement as the identification of parameters within a model of the observed. This means that the model is of an operational or functional form in which the measures, the parameters, are operated upon to derive meaning. This indicates that the form of the model is analogous to the mathematical constructs of functions. In contrast, the OOMM concept of the model need only identify the meaningfully distinguished cases, and so need only be a categorization type of model, rather than a functional operational model although the latter may be the form of the model in the OOMM. The OOMM model may include functions and operations to transform data but such functions and operations are internal to the model and its construction of the analysis of the raw data obtained through application of the measurement instruments prescribed by the model.

The definition of measurement is not opposed to the Hegelian dialectic conception of measurement introduced by Sacerdoti et al. [30] although the routine use of a measurement model uses, primarily, Sacerdoti et al.'s [30] stages 2 and 3. The Sacerdoti et al. [30] dialectic, including stage 1, is used to form the OOMM class conception that relates to any particular measurement scenario since the OOMM class conception is constructed through investigation and consideration of the issues raised by Sacerdoti et al.

Where Sacredoti et al. [30] refer to a dialectic process of observation, organization of experimental situation and representation of results, one may question whether the traditional understanding of the scientific method should be discussed. The traditional scientific method involves a loop of hypothesis formulation, testing and refinement, leading to an un-refuted hypothesis that is treated as fact. The traditional view of the scientific method is cyclical, in which an hypothesis is formed, presented with a test and the outcome leads to a refined hypothesis, which becomes the starting point of a new cycle. The process begins with a general observation phase, Sacredoti et al.'s 'historical phase', which is required to generate the initial hypothesis. Then the conception of the process changes in Sacredoti et al., who hold that there is a presentation of a test, the antithesis, to the hypothesis. The result is not a refutation or non-refutation, but rather the generation of a refined hypothesis. Consequently, the Sacredoti et al. dialectic view of the development of the capacity to measure is Hegelian rather than cyclic. The radical contribution of Sacredoti et al. is that the process of measurement is seen as part of a dynamic understanding development situation, rather than as a knowledge delivery mechanism in a static situation.

7. Conclusion

This paper has reviewed earlier definitions of measurement in relation to the concept of measurement that those definitions embody. A new definition of measurement was proposed which emphasizes the role of measurement in classification of the particular observed according to a structure of reality described in a model of the measurement scenario, which has the characteristics of the object oriented model of measurement requirements upon a model of a measurement scenario.

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