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Can we dispense with the notion of 'true value' in metrology?

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Since the beginnings of error theory and its first developments by Gauss and Laplace, a physical quantity is characterized by its 'true value', a value that would have been obtained, had an ideal perfect measurement been processed. In the second half of the twentieth century, this conception of measurement has been challenged from different perspectives, conducting to a position where the concept of 'true value' loses its central place, if not becomes avoidable.

Can we dispense with the notion of 'true value' in measurement? If so, what would measurement be designed for? If not, what precisely would be the philosophical meaning of such a concept, in particular with respect to (scientific) 'truth'? This paper aims at exploring two essential arguments developed against 'true value' in recent metrology texts, among which especially the *Guide to the expression of uncertainty in measurement*, henceforth abbreviated *GUM*,[1] and the *International Vocabulary of Metrology*, respectively *VIM*,[2] two international guidance documents planned to harmonize the terms and practices in measurement science. The first argument consists in pointing out that 'true value' cannot be the proper aim of measurement since it is a forever unknowable ideal. The second argument revolves around the impossibility, in many physical cases, to conceive of a non-unique true value for a given quantity.

It is argued that two different modes of analysis can be distinguished within the critique: an operational mode and a metaphysical mode. By separating these two modes, I defend the idea that metrologists don't actually dismiss the concept of 'true value' as long as they don't adhere to some kind of anti-realism.

The two arguments are presented successively and discussed in relation to their consequence on the notion of 'true value'. The conclusion is dedicated to the relationship between 'true value' and scientific realism.

1 An epistemic turn in metrology

1.1 From 'error approach' to 'uncertainty approach'

In the traditional approach of measurement that dominated metrology during the first half of the twentieth century, the quality of a measurement procedure was primarily evaluated in terms of its *accuracy*, namely its propensity to produce results with small 'measurement errors'. The latter are defined[3] as the numerical deviation between an actually obtained result and the true value of the measured quantity:

$$\epsilon = x - v \qquad \begin{cases} \epsilon = \text{measurement error} \\ x = \text{(known) measurement result (value actually obtained)} \\ v \;\; = \text{(unknown) true value of the quantity} \end{cases} \tag{1}$$

In such an approach, measurement is conceived as the determination of an estimate of the quantity's true value with the best closeness of agreement possible. Equation (1) shows how

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[1] Joint Committee for Guides in Metrology (JCGM), *Evaluation of measurement data - Guide to the expression of uncertainty in measurement* (Sèvres: JCGM, 2008).

[2] Joint Committee for Guides in Metrology (JCGM), *International vocabulary of metrology - Basic and general concepts and associated terms (VIM)* (Sèvres: JCGM, 2012).

[3] See for example the *VIM* for a current definition of the term: Joint Committee for Guides in Metrology (JCGM) (2012), p. 22.

measurement error and true value are consubstantially tied. For these reasons, the traditional approach is often designated as an 'error approach' and contrasted with a more recently developed 'uncertainty approach',[4] in which the concepts of 'true value' and 'measurement error' are explicitly challenged. In the 'uncertainty approach', it is argued that their use should be dismissed, as they correspond to ideal concepts, ultimately unknowable.[5] Resting on pragmatic grounds, proponents of the 'uncertainty approach' argue that a proper measurement method, instead of trying to achieve a somewhat metaphysical 'accuracy',[6] should rather only be described through an (epistemic) *uncertainty*, defined as a range of values that are thought be *reasonably* attributed to a quantity.

> The objective of measurement in the Uncertainty Approach is not to determine a true value as closely as possible. Rather, it is assumed that the information from measurement only permits assignment of an interval of reasonable values to the measurand, based on the assumption that no mistakes have been made in performing the measurement.[7]

This aspect is particularly explicit in the evolution of the definition of measurement uncertainty from the first to the third editions of the *VIM*. From 'an estimate characterizing the range of values within which the true value of a measurand lies',[8] it becomes a 'non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used':[9] the true value has disappeared.

To summarize, the difference between the two approaches is primarily a matter of aim. They both share a *fixed* quantity as their common object of inquiry. They differ, however, on whether they aim or not at the true value of this given quantity. This is a change in focus, from the measured object itself to the practical issues related with the application of measurement results. At the same time, 'truth', considered as a somewhat illusory objective, is replaced by the more concrete and accessible *adequacy* with a given goal.[10] This particular evolution participates to a broader movement that we may designate as an 'epistemic turn' in the field of metrology, involving a change of attitude towards the way measurement is considered to be related to knowledge. Another feature of this shift is the transition from frequentist statistics to Bayesian statistics in metrology.

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[4] Joint Committee for Guides in Metrology (JCGM) (2012), p. viii.

[5] Joint Committee for Guides in Metrology (JCGM) (2008), p. 3.

[6] I refer here to Tal's five notions of measurement accuracy. The meaning of measurement accuracy in metrology corresponds to Tal's 'metaphysical accuracy': Tal, E., 'How Accurate is the Standard Second?', *Philosophy of Science*, 78:5 (2011), pp. 1082–1096.

[7] Joint Committee for Guides in Metrology (JCGM) (2012), p. x. At this point one can identify 'measurand' with 'quantity'. We will see later how the two terms differ. See L. Mari's contribution to this volume for a more detailed development on the notion of 'measurand'.

[8] International Organization for Standardization (ISO), *International vocabulary of basic and general terms in metrology* (1984), p. 16.

[9] Joint Committee for Guides in Metrology (JCGM) (2012), p. 25.

[10] This move was already tackled in Mari, L., 'Epistemology of measurement', *Measurement*, 34 (2003), pp. 17–30, especially on p. 18.

1.2 From frequentist statistics to Bayesian statistics in measurement

The technical machinery of uncertainty analysis uses probabilities since the first developments of a ‘theory of errors’ in the late eighteenth century. However, if the probabilistic interpretation of measurement results achieved a first maturation in 1827 with what Stigler calls the ‘Gauss-Laplace synthesis’,[11] metrologists are still faced today with two approaches grounded on incompatible interpretations of probability, namely a frequentist and a Bayesian one.

In the frequentist approach, especially dominant in metrology in the first half of the twentieth century, probabilities are long-run relative frequencies of occurrence of the different possible issues of a repeatable event. The probabilities characterize not a measurement result in itself, but the measurement as a *physical process* of generation of experimental data. The potential outcome of each individual measurement is considered as the result of a random trial from a statistical population. A natural candidate for probability statement is here the statistical distribution of errors generated in a certain given experimental protocol. The idea underlying the error analysis of the measurement process consists in separating what is due to the ideal phenomenon under examination (encompassed by the true value of the quantity) from what is caused by the material and theoretical contingencies of the necessarily imperfect experimental procedure (the ‘measurement error’). The statistical analysis of error, given some hypotheses – embodied within a *data model* postulating a general behaviour of measurement errors – enables a statistical inference, formulated in probabilistic terms, about the possible value of the measurand. The frequentist analysis of error shows how the true value acts in the statistical machinery as a regulative ideal that governs how actual values are eventually attributed to the measurand.

However, the frequentist method utterly fails to take into account the so-called ‘systematic errors’ from a probabilistic standpoint. By nature, this type of error does not vary under repeated measurements. Therefore, it is transparent to any statistical analysis based on frequencies. Proponents of a Bayesian approach in metrology therefore argue that physical probabilities cannot provide a complete probabilistic account of measurement and conclude that epistemic probabilities should be preferred. This position about the role of probability in measurement grew substantially in the latest decades of the twentieth century.

In the Bayesian case, every quantity or parameter of a model – even the fixed values that are systematic errors – may be subject to a probabilistic judgement through a probability distribution, the argument of which being a possible value of the quantity or the parameter, and the corresponding probability density expressing the *degree of belief* granted to the given possible value (in a subjectivist view) or the amount of knowledge that one possesses about the quantity (in an objectivist view). In any case, the subjective character of measurement is generally acknowledged, and even claimed by proponents of the Bayesian approach.[12] Uncertainties and quantity values are inferred from the updating of prior knowledge, given empirical data, by

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[11] Stigler, S., *The History of Statistics: The Measurement of Uncertainty before 1900* (Cambridge, MA: Belknap Press of Harvard University Press, 1986), p. 158.

[12] Bich, W., ‘From Errors to Probability Density Functions. Evolution of the Concept of Measurement Uncertainty’, *IEEE Transactions on Instrumentation and Measurement*, 61:8 (2012), pp. 2153–2159, on pp. 2155–2156: ‘[the classical] attitude is based on the illusion that subjectivity can be totally avoided in measurement, whereas it permeates much of it.’

using Bayes's theorem. A measurement result may then take the form of a probability distribution expressing a statement about *the given knowledge (or belief) of a group* about the value of the quantity. The consequence is a displacement of the subject-matter of a measurement result, from the state of the measured object itself to the state of knowledge of the experimenter. For these reasons, the use of Bayesian methods is at the heart of an ongoing epistemic turn in metrology.

1.3 Two levels of discussion

To summarize, the evolution of the conception of measurement in metrology in the second half of the twentieth century is mainly characterized by two entangled features:

- A change of focus. The search for metaphysical accuracy, characterized by inaccessible ideals like 'error' and 'true value', is replaced by a formulation centred on the epistemic notion of 'measurement uncertainty'.
- A change in representation. With the growth of the Bayesian viewpoint, a measurement result does not represent the *physical* state of the quantity measured any more. Instead, it formulates a claim about a personal or interpersonal state of knowledge quantified by epistemic probabilities.[13]

Proponents of the epistemic view argue that the traditional objectives are illusory, as it is impossible to formulate a result otherwise than by a statement of present knowledge. In return, defenders of the traditional view, while acknowledging the latter's limits,[14] claim that the Bayesian approach does not enable us to anchor measurement and science in reality.

I will not address this controversy here: rather, my aim is to focus on the change of status that this epistemic turn in metrology generates on the concept of 'true value' in measurement. The latter is illustrated by the following statement by Ehrlich, Dybkaer and Wöger: 'if the true value … is not knowable in principle, then the question arises whether the concept of true value is necessary, useful or even harmful!'[15] If the true value is not knowable, what incentives are there to actually use it in scientific theories? I believe that two separate questions can be distinguished concerning the role of the true value in measurement.

(Q1) A metaphysical question: what is the link between 'true value' and *truth* in measurement?

(Q2) An operational question: does measurement need, *as an operation*, a parameter at least similar to 'true value'? In other words, do metrologists actually (need to) *use* anything close to a concept of true value?

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[13] See for example Estler, W. T., 'Measurement as Inference: Fundamental Ideas', *Annals of the CIRP*, 48:2 (1999), pp. 611–631, on p. 618: 'A great deal of time can be wasted in heated arguments concerning the exact form of the [probability density], which describes not reality in itself but only one's knowledge about reality.'

[14] For a recent attempt to defend the traditional approach by resolving its internal difficulties, see Willink, R., *Measurement Uncertainty and Probability* (Cambridge: Cambridge University Press, 2013), especially pp. 72–81.

[15] Ehrlich, C., Dybkaer, R., and Wöger, W., 'Evolution of philosophy and description of measurement (preliminary rationale for VIM3)', *Accreditation and Quality Assurance*, 12 (2007), pp. 201–218, on p. 209.

I argue that the epistemic standpoint does not in fact dismiss the true value at the operational level, but merely tries to dissimulate it. However, the metaphysical issue remains undecided.

1.4 The operational problem

Let us answer to the second question first. I will stick here to the definition of 'measurement' given in the *VIM*: 'process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity'.[16] The assignment of a numerical value to a quantity is certainly not *arbitrary*: it is made following certain *rules* deriving from a *data model* embedded into the whole process.

In the frequentist model, the data model describes the probability of each *potential outcome* of the measurement process through a counterfactual long-run frequency of occurrence, would the measurement be repeated infinitely. This probability is *conditioned* on a fixed unknown parameter, the so-called 'true value' of the quantity. The frequentist model then governs the assignment of a value to the quantity by stating that the chosen value to be assigned should be the one that maximizes the probability of occurrence of the empirical data sample actually obtained, *would the true value be equal* to this assigned value, *given the hypotheses of the data model.*

The Bayesian model of data describes the experimenter's state of knowledge through a probability distribution. Any empirical data enables the revision of this probability distribution through Bayes's formula. The likelihood function used in Bayes's formula is itself conditioned on the possible values of the true value of the quantity.[17]

As a consequence, it appears impossible, in both approaches, to completely dismiss the *use* of the true value in the value-attribution processes, since this concept appears in the *equations* governing these processes.[18] My provisional conclusion is therefore that the concept of 'true value' remains used in current metrology, even if it disappears from the *expression* of the result itself. However, question (Q1) relative to the philosophical meaning of this parameter remains open.

1.5 The metaphysical problem

Still, even if the notion of 'true value' does intervene in the measurement models actually used by metrologists, one may argue that the denomination is misleading and that the term only designates a useful mathematical tool without any relationship with actual 'truth'. A straightforward way to understand the notion of 'true value' is provided by the correspondence theory of truth attached to a realist account of science: the true value is true in virtue of its correspondence with an actual element of reality. However, following classical philosophical discussions, 'true value' could be interpreted in a weaker sense, as a theoretical term in a theory *adequate*

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[16] Joint Committee for Guides in Metrology (JCGM) (2012), p. 16.

[17] Lira, I., *Evaluating the Measurement Uncertainty: Fundamental and Practical Guidance* (Bristol and Philadelphia, Institute of Physics Publishing, 2002), p. 176.

[18] Some alternative approaches try to make the true value disappear in the equations themselves. See for example the IEC approach described in Ehrlich et al. (2007), pp. 213–217.

with the results of empirical investigation. In such an empiricist account, all metaphysical reference to 'reality' and 'truth' is rendered unnecessary. In that case, the qualifier 'true value' would indeed be a misnomer, to which could be preferred 'target value',[19] 'theoretical value',[20] or mere 'value', as is the choice made in the *GUM*.[21]

The central claim regarding this issue is the unknowable character of the true value. The emphasis on the unknowable character of the true value displays an empiricist position eager to purge measurement theory from its metaphysical overlay. It is unlikely that this debate may be settled within metrology practice itself: it is rather a question of general philosophy of science. Certainly, the epistemic turn in metrology could be interpreted as an inclination to anti-realism from metrologists. But this does not seem convincing: metrologists and scientists usually tend to stick to a local, moderate realism, such as the one Wimsatt sketches.[22] The status of the concept of 'true value' in metrology still stands as an interesting example of the ramifications of the problem of realism within scientific practice: do scientists apply a specific (personal) philosophy? Do they manage to practice science without any metaphysical or philosophical preconception?

Eventually, the empiricist stance described in this section is only one side of the critique of 'true value' that can be found in recent metrology documents. This critique is actually twofold: its other side is directed towards the uniqueness of the true value of a quantity (in a chosen system of units): if a quantity cannot be said to have a unique true value, how could anyone of them qualify as the true value ? Although both issues are not clearly separated in recent metrology texts, I believe that they should be considered as two essentially independent problems. The latter relates to a notion recently designated as 'definitional uncertainty', which expresses an idea that has been foreseen for several decades.

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[19] Eisenhart, C., 'Realistic Evaluation of the Precision and Accuracy of Instruments Calibration Systems', *Journal of Research of the National Bureau of Standards - C. Engineering and Instrumentation*, 67C:2 (1963), pp. 161–187, on p. 171. See also Willink (2013), p. 6.

[20] Robert-Schwartz, C. and Treiner, J., 'Incertitudes des mesures de grandeurs', in J.-P. Kahane (ed), *Commission de réflexion sur l'enseignement des mathématiques, annexe sur la statistique* (2003), pp. 6–17, on p. 8.

[21] 'The term "true value of a measurand" … is avoided in this Guide because the word "true" is viewed as redundant', Joint Committee for Guides in Metrology (JCGM) (2008), p. 50. The unknown true value of a quantity contrasts with the *actually assigned value* of that quantity, the latter being the known end product of a measurement process, typically destined to theory testing or decision making. In the *GUM*, any reference to a true value is dismissed (for the reasons already mentioned in this paper), and the emphasis is put on the actually assigned value (see p. 59). Since no differentiation between the true value and the assigned value is then needed any more, the choice was made in the *GUM* to designate the assigned value directly by the mere term 'value'. However, this leads to great misunderstandings and to a lack of clarity since, as we showed, an equivalent to the true value is needed, at least as a model parameter, in the value-attribution processes. The choice made in the 2008 edition of the *VIM* to maintain the traditional categories '(quantity) value' and 'true (quantity) value' seems, in this regard, a much better decision.

[22] Wimsatt, W. C., *Re-Engineering Philosophy for Limited Beings: Piecewise Approximations to Reality* (Cambridge, MA: Harvard University Press, 2007), pp. 94–95.

2 Definitional uncertainty

2.1 About definitional uncertainty: Definitions

What is 'definitional uncertainty'? It is essential here to stress the importance of the concept of 'measurand' that is the object of enquiry of a measurement. Since the 2008 edition of the *VIM*, it is acknowledged that the measurand is not to be defined as a 'particular quantity (subject to measurement)'[23] but as an *intended* quantity, the 'quantity intended to be measured'.[24] In order to understand the articulation of 'true value', 'measurand' and 'definitional uncertainty', it is useful to quote the following development from the *GUM* in full:

> Suppose that the measurand is the thickness of a given sheet of material at a specified temperature. The specimen is brought to a temperature near the specified temperature and its thickness at a particular place is measured with a micrometer. The thickness of the material at that place and temperature, under the pressure applied by the micrometer, is the realized quantity.
>
> The temperature of the material at the time of the measurement and the applied pressure are determined. The uncorrected result of the measurement of the realized quantity is then corrected by taking into account the calibration curve of the micrometer, the departure of the temperature of the specimen from the specified temperature, and the slight compression of the specimen under the applied pressure.
>
> The corrected result may be called the best estimate of the 'true' value, 'true' in the sense that it is the value of a quantity that is believed to satisfy fully the definition of the measurand; but had the micrometer been applied to a different part of the sheet of material, the realized quantity would have been different with a different 'true' value. However, that 'true' value would be consistent with the definition of the measurand because the latter did not specify that the thickness was to be determined at a particular place on the sheet. Thus in this case, because of an incomplete definition of the measurand, the 'true' value has an uncertainty that can be evaluated from measurements made at different places on the sheet. At some level, every measurand has such an 'intrinsic' uncertainty that can in principle be estimated in some way.[25]

During the measurement process, the definition of the measurand is *realised* by a *particular* quantity, but *could have been realised* by other particular quantities also consistent with the incomplete definition of the measurand. We may then refer to the definition of true value in the latest edition of the *VIM*: 'quantity value consistent with the definition of a quantity'.[26] Accordingly, the value of each quantity consistent with the definition of the measurand may be said to be a 'true' value of the measurand. As a consequence, a measurand is not characterized by a unique true value, but by a *range* of (equivalently consistent) true values. Thus,

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[23] This is the definition of the 1993 edition of the *VIM*, see International Organization for Standardization (ISO), *International vocabulary of basic and general terms in metrology* (1993), p.20.

[24] Joint Committee for Guides in Metrology (JCGM) (2012), p. 17.

[25] Joint Committee for Guides in Metrology (JCGM) (2008), pp. 49–50.

[26] Joint Committee for Guides in Metrology (JCGM) (2012), p. 20.

what was called ‘intrinsic uncertainty’ in the *GUM* and in the 1993 edition of the *VIM* and is now designated as ‘definitional uncertainty’ is defined as follows: ‘component of measurement uncertainty resulting from the finite amount of detail in the definition of a measurand’.[27]

Documents like the *GUM* and the *VIM* do not clearly distinguish issues of knowability (discussed in section 1) from issues about definitional uncertainty. However, problems of non-uniqueness of the true value of a quantity were already acknowledged in traditional frequentist approaches.[28] Therefore, it would be preferable to consider knowability and definitional uncertainty as two separate issues.

2.2 Estimating definitional uncertainty

Measurement uncertainty is quantitatively evaluated through a global ‘uncertainty budget’ summing up all identified sources of uncertainty. As a component of measurement uncertainty, definitional uncertainty must be accounted for quantitatively. However, the *GUM* does not provide any method of evaluation of this type of uncertainty. In fact, it even immediately gets rid of the problem by stating the hypothesis of ‘an essentially unique [true] value’.[29]

There would not be much interest here to enter into a technical discussion about the quantitative evaluation of definitional uncertainty and its integration into the overall statistical theory of uncertainty analysis. However, it is worth pointing out here the *epistemic* nature of definitional uncertainty. Definitional uncertainty *is* an uncertainty because it is related to a given body of knowledge (and not directly to a state of nature): it describes how one *believes*, or knows, the definition of the measurand to be incomplete. If one’s body of knowledge evolves, then the definitional uncertainty about a given measurand is likely to change. Definitional uncertainty is not an intrinsic measure of the incompleteness of the definition of the measurand.

In the end, definitional uncertainty is related to the (estimated or measured) width of the range of values consistent with the definition of the measurand, or, more accurately, to the range of true values of the quantities that are believed to realise the definition of the measurand, given an available body of knowledge. This also implies that definitional uncertainty is *not* a consequence of an imperfection of one’s body of knowledge (if I ask for a fruit, one may give me an apple or an orange, which equally match what I asked for – this doesn’t mean that I don’t know how to distinguish between an apple and an orange). On the contrary, a greater body of knowledge will reveal new components of definitional uncertainty to take account of. This marks an important contrast with the ordinary notion of measurement uncertainty which qualifies *limits* of knowledge.[30]

2.3 Two main issues generated by definitional uncertainty

Definitional uncertainty brings two philosophical difficulties. What is the meaning of a ‘non-unique true value’? More explicitly, how can different values for a same quantity be said to

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[27] Joint Committee for Guides in Metrology (JCGM) (2012), p. 25.

[28] See for example Eisenhart (1963), p. 171.

[29] Joint Committee for Guides in Metrology (JCGM) (2008), p. 1.

[30] As underlines Treiner, ‘uncertainties related to the variability of phenomena … are stable and do not decrease when our knowledge progresses’, in Treiner, J., ‘Variabilité, incertitude, erreur’, *Bulletin d’Union des Physiciens*, 105:930 (2011), pp. 9–14, on p. 14.

be ‘true’ at the same time? The denomination ‘*a* true value’ once used in the *VIM*[31] to bypass the problem is clearly counter-intuitive.[32] Moreover, non-unique true values conflict with the traditional use of physical equations, which express both a physical relationship between properties and a numerical relationship between the (true) values of the quantities involved.[33] Here, we are confronted again with the two types of issues described in section 1.3: a metaphysical issue about the *truth value* of “true value” and an operational issue about the role of numerical equations to express physical laws. The next subsection is an attempt to show that the possible answers to these issues are rooted in a separation between the fundamental and the phenomenological.

2.4 Reconciling definitional uncertainty and true value: Individuation of objects and quantities

The measurement of a given quantity requires us to build a model of the object under measurement,[34] which involves a minimal arbitrary amount of *idealisation* and will leave aside some known effects affecting the measurement.In the case of the paradigmatic example of the measurement of the length of a table, the definition of the measurand is conditioned on the idea that the table may be modelled as a geometrical figure (typically a rectangle parallelepiped), the former being an idealisation of the table as a physical object.[35] Once conceived of as a geometrical figure, the model of the table involves unique length and width. However, definitional uncertainty expresses how it is impossible to force the reality into the model by measuring a unique value. Thus, the role of definitional uncertainty seems to be at the interface between the physical object and the model.

In many cases, the physical object under measurement is a complex and composite entity that we want to describe as an isolated individual. Let us take the example of the measurement of the length of a pen. A measurand definition would usually be ‘the length of the pen’ without any more specification. However, a pen occupies more space when held vertically than horizontally, because of gravitational effects (a difference of several micrometers).[36] A more specific definition of the measurand could then be either its ‘horizontal length’ or its ‘vertical length’. Yet, in that case we generally consider that both definitions remain two instances of the *same* quantity in different conditions of observation. What ties these two measurand definitions is the identification of ‘the pen’ as an individual, a concrete object clearly identified.[37] In general, adding up specifications to the definition of the measurand in order to reduce definitional

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[31] International Organization for Standardization (ISO) (1993), p. 16.

[32] See also Mari’s objections in Mari (2003), p. 22.

[33] See De Courtenay’s contribution to this volume for a development on the dual role of physical equations. de Courtenay, N., ‘The Double Interpretation of the Equations of Physics and the Quest for Common Meanings’, in O. Schlaudt and L. Huber (eds), *Standardization In Measurement: Philosophical, Historical And Sociological Issues* (Pickering & Chatto, 2015), pp. 53–68

[34] Giordani, A. and Mari, L., ‘Measurement, Models, and Uncertainty’, *IEEE transactions on instrumentation and measurement*, 61:8 (2012), pp. 2144–2152, on p. 2147.

[35] This reflects the conception of ‘mathematical idealisation’ described in McMullin, E., ‘Galilean idealization’, *Studies in History and Philosophy of Science*, 16:3 (1985), pp. 247–273, on pp. 248–254.

[36] I owe this example to Marc Priel, from the LNE (Laboratoire National de métrologie et d’Essais, Paris).

[37] It should be important here to mention that Tal has identified quantity individuation among three major epistemological problems about measurement: Tal, E., ‘The Epistemology of Measurement: A Model-Based Account’

uncertainty will result in a progressive detachment from the individual itself. Moreover, the pen only exists at a macroscopic scale: once one zooms in into its molecular details, it becomes impossible to distinguish a clear frontier separating the pen from its environment, and thus to even identify an individual. In the end, the identification and isolation of an individual such as 'the pen' is precisely at the cost of a definitional uncertainty: there is a trade-off between individuation and definitional uncertainty. It is because we want to measure the length of 'the pen' in itself, and not to describe a microscopic display of elementary particles, that definitional uncertainty is inevitable at the phenomenological scale. In that case, definitional uncertainty characterizes the fact that, *in our theories or models*, the measurand taken in consideration is a complex individual that presents a *substructure*.

By contrast, the *VIM* states that 'in the special case of a fundamental constant, the quantity is considered to have a single true quantity value.'[38] No definitional uncertainty is attached to fundamental quantities, not because there actually isn't any underlying substructure, but because there exists no *known* substructure: this again highlights the epistemic nature of definitional uncertainty, related to a given body of knowledge and not to the *actual* existence of a substructure. This whole account suggests a double classification of quantities: between phenomenological and fundamental ones on the one hand, and between state variables and constants on the other hand (see table 1). The epistemic nature of definitional uncertainty implies that the status of quantities is not frozen once and for all. Quantities like the mass of the electron (or even Planck's constant) are only fundamental *in the present state of our mainstream theories*: they might not be so in candidate theories such as string theory.

	state variables	properties ('constants')
phenomenological	length of a table mass of a table	electrical conductivity of copper density of water
fundamental	quantum state of a given electron	mass of the electron Planck's constant

Table 1: A suggestion for a classification of quantities.

Definitional uncertainty arises at a phenomenological level, when measurement aims at entities that are not fundamental in our theories. This classification highlights how definitional uncertainty is somehow tied to the issue of reductionism in science, and particularly here through the distinction between fundamental and phenomenological laws of physics. Crucially, phenomenological laws are *approximate* statements – they are only true in a model of phenomena that incorporates idealisations and approximations. Measuring the resistance of a resistor requires a model of this resistor in which it is (for example) assumed to obey Ohm's phenomenological law.[39] What happens here can be put on a par with what happened earlier when the table was modelled as a geometrical figure. *In the models*, the phenomenological laws

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(PhD dissertation, University of Toronto, 2012), pp. 48–92. This is not the issue that I address here, although I hold definitional uncertainty, and the concept of 'measurand', to be strongly relevant to it.

[38] Joint Committee for Guides in Metrology (JCGM) (2012), p. 20.

[39] See for example Giordani and Mari (2012), p. 2147–2149.

are true and the quantities involved have single values. At the same time, phenomenological laws *are* approximate and phenomenological quantities involved in these laws are associated with a finite definitional uncertainty.

2.5 Required accuracy of measurement

In the end, the status of the quantities and the equations involved depends on the intentions and the purposes of the experimenter, as underlined by Giordani and Mari:

> Of course, such idealisation is not imposed to the modeler, who, by means of these models, actually decides the concepts (of the object under measurement and the measurand) that she considers appropriate in dependence on her goals.[40]

As Tal explains,[41] measurement uncertainty arises from a progressive 'de-idealisation' of an idealised measurand definition towards the realised quantity. However, definitional uncertainty differs in this regard. It corresponds to the amount of idealisation *not* introduced in the definition of the measurand, but that would have been necessary, given the known physical effects affecting the object under measurement, had one wanted a finer measurand definition, adapted to different purposes. A crucial step resides in acknowledging that, in ordinary measurement, fundamental issues are of *no* interest: the microscopic structure of a pen is of no importance in ordinary measurements about this pen. What matters is the identification of objects at a phenomenological level. This is illustrated by the following quote from the *VIM*:

> In practice, the required specification or definition of the measurand is dictated by the required accuracy of measurement. The measurand should be defined with sufficient completeness with respect to the required accuracy so that for all practical purposes associated with the measurement its value is unique … EXAMPLE If the length of a nominally one-metre long steel bar is to be determined to micrometre accuracy, its specification should include the temperature and pressure at which the length is defined… However, if the length is to be determined to only millimetre accuracy, its specification would not require a defining temperature or pressure or a value for any other defining parameter.[42]

To conclude, the operational issue generated by definitional uncertainty, that is the compatibility of non-unique true values with physical laws, is defused by noticing that incomplete measurand definitions correspond to phenomenological quantities involved only in phenomenological, henceforth *approximate* laws. Definitional uncertainty then corresponds to a certain 'resolution' at which the phenomenological law is supposed to work, given some intentions represented by what is called in the *GUM* the 'required accuracy of measurement'. The metaphysical issue, though, is more complicated and is rooted in general philosophy of science. It loops back to an issue already brought up in the discussion of the epistemic turn in metrology in section 1. I turn to it in the conclusive section.

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[40] Giordani and Mari (2012), p. 2148.

[41] Tal (2011), p. 1090.

[42] Joint Committee for Guides in Metrology (JCGM) (2008), p. 4.

3 Conclusion

The previous study of the critiques addressed against the notion of true value within the field of metrology has unravelled two distinct issues: an operational and a metaphysical issue. I first answer to the operational question: does measurement need a concept of 'true value' in order to be processed? Although I do not *a priori* dismiss potential alternative attempts to bypass the use of such a concept, I nonetheless argue that none of the main critiques addressed within metrology really establishes that such a use should be avoided and none of them explains how this could be done. On the contrary, the examination of the critique concerning knowability (in section 1) enables us to reconsider how the true value is actually used in value-attribution processes, making it a central regulative ideal despite being unknown. Then, definitional uncertainty (analysed in section 2) reveals the importance of the identification of a target in measurement[43] (illustrating how measurement is a goal-driven operation) and shows that the concept of 'true value', at a phenomenological scale, can only be understood by invoking a notion of 'approximate truth'.[44]

If the operational problem is defused, then the critique against the true value is reduced to the metaphysical issue alone. Despite their methodological character, the *GUM* and the *VIM* reveal some inner 'quasi-philosophical considerations'[45] where the position of metrologists about the true value sounds like a variety of empiricism. But is the true value only a tool? The term might be understood in two different ways:

(1) {true} {value of a quantity}

(2) {true value} {of a quantity}

If the true value is understood as 'a value that is true' (case 1) then it typically points to the correspondence theory of truth. Otherwise, 'true value' may be understood as being only a denomination (case 2) where 'true' is not a qualifier of the value (as was discussed in section 1.5). In this case, the true value might be a useful concept for theoretical construction, but the phrase can only be understood as a whole and has nothing to do with 'true' 'value' taken separately. In the latter case, the true value may then be a statistical parameter, for example the expectancy of some probability distribution, and could for instance be replaced by the term 'theoretical value', in harmony with van Fraassen's empiricist account. This issue is rooted in the opposition between scientific realism and instrumentalism. Concerning measurement and quantities, Michell has defended a realist position.[46] The representational view sees measurement only as an analogy of structures between nature and numbers. Mari tempers these two approaches and sees measurement as being both an assignment (of values belonging to a symbolic world) and

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[43] As underlines Treiner, 'physical quantities only have a meaning at a certain scale and for a given use', Treiner (2011), p. 12.

[44] I owe this expression to Barberousse, A., 'La valeur de la connaissance approchée. L'épistémologie de l'approximation d'Émile Borel', *Revue d'histoire des mathématiques*, 14:1 (2008), pp. 53–55.

[45] Priel, M., 'Guide du vocabulaire de la métrologie: le concept de la valeur vraie fait débat', *Mesures*, 804 (2008), pp. 20–23, on p.20.

[46] Michell, J., 'The logic of measurement: a realist overview', *Measurement*, 38 (2005), pp. 285–294.

a determination (of a state of nature).[47] What seems important here is to show that a notion like 'true value' does not necessarily suggest 'the world' to be quantitative *in essence*, but is minimally attached to the truth of scientific claims, scientific theories and physical laws that are expressed through mathematical equations. In physics, quantities are commonly used in equations known to be false: the case of definitional uncertainty shows the importance of a notion of 'approximate truth' if some kind of realism is to be adopted.

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[47] See in particular Mari, L., 'The role of determination and assignment in measurement', *Measurement*, 21:3 (1997), pp. 79–90 as well as Mari, L., 'Beyond the representational viewpoint: a new formalization of measurement', *Measurement*, 27:2 (2000), pp. 71–84 and Mari, L., 'The problem of foundations of measurement', *Measurement*, 38 (2005), pp. 259–266.

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