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On quantity, value, unit, and other terms in the JCGM International Vocabulary of Metrology

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Abstract
The Joint Committee for Guides in Metrology (JCGM) is in the process of revising the third edition of the International Vocabulary of Metrology (VIM3). Open discussion of the concepts, terms, and definitions used in metrology by the international community in peer reviewed journals could be constructive inputs to the JCGM deliberations on revising the VIM3. The VIM3 definitions of quantity, quantity value, unit of measurement, measurement standard, measurement, uncertainty in measurement, true quantity value, coverage interval, coverage probability, and metrology are reviewed. Some defects are observed. Proposals are offered to stimulate discussions which may lead to better concepts, terms, and definitions for metrology.

Keywords: measurement, measurement standard, metrology, quantity, quantity value, uncertainty in measurement, unit of measurement

(Some figures may appear in colour only in the online journal)

1. Introduction

This paper is about some concepts, terms, and definitions in the International Vocabulary of Metrology published (in 2008) by the Joint Committee for Guides in Metrology (JCGM) [1] and referred to as the JCGM 200 [2]. The JCGM 200 is also known as the VIM3 (the third edition of VIM). On 11 January 2021, the JCGM posted the first Committee Draft of a fourth edition of the VIM (VIM4-1CD) on the website of the International Bureau of Weights and Measures (BIPM) [1]. National metrology institutes (such as the U.S. National Institute of Standards and Technology, NIST) have been invited to submit official feedback on the VIM4-1CD to the BIPM. The contents of VIM4-1CD cannot be quoted. This study of the VIM3 would remain relevant if the VIM4 turns out to be like the VIM4-1CD.

The first edition of the International Vocabulary of Metrology (VIM1) was published in 1984 [3]. The second edition of the VIM (VIM2) was published in 1993 [4]. The VIM2 was paired with the Guide to the Expression of Uncertainty in Measurement (GUM) [5]. The terms and definitions used in the GUM are a subset of the VIM2 [5]. The JCGM was formed in 1997 to maintain and promote the use of GUM and VIM2. A rationale for revising the VIM2 was presented [6, 7]. A rationale for revising the VIM3 has not appeared. However, the JCGM had announced (in March 2019) on the website of the BIPM that the VIM4 would consist of minimally revised versions of the five chapters of VIM3, and a new chapter 6 for nominal properties. The VIM4-1CD is consistent with that announcement.

The JCGM is composed of representatives from eight esteemed international scientific organizations [1]. Thus, the JCGM 200 carries the authority of those organizations. However, the JCGM 200 has many shortcomings. The purpose of this paper is to stimulate open discussion of the concepts, terms, and definitions used in metrology by the international community in peer reviewed journals. Such discussions could be constructive inputs to the JCGM deliberations on revising the JCGM 200 (or its later editions).

The terms and definitions used in metrology must clarify the concepts. We studied the JCGM 200 definitions of seven core metrological terms (CMT): quantity, quantity value, unit of measurement, measurement standard, measurement, uncertainty in measurement, and metrology. Study of the uncertainty in measurement required investigation of three related terms: true value of a quantity, coverage interval, and coverage probability. Terms are labels of concepts. We observed the following types of defects: (a) disagreement with commonly understood meanings by a majority of educated people, (b) intermixing different concepts, (c) missing distinguishing characteristics of a concept, (d) ignoring essential concepts, (e) ill-defined, and (f) undermining the concept of uncertainty in measurement established by GUM. This criticism does not undermine the important additions and improvements in the JCGM 200 over the earlier (pre-JCGM) editions, especially the VIM1. We offer proposals to stimulate discussions which may lead to better concepts, terms, and definitions for metrology.

Section 2 is a review of the JCGM 200 definitions of seven CMT and three related terms. Section 3 offers suggestions to improve the JCGM 200 concepts, terms, and definitions. Per the JCGM 200, the idea of 'true value of a quantity' is kept in the GUM as the objective (target) of measurement. Section 4 is a discussion of the term 'true value of a quantity' as the target of measurement. A summary appears in section 5, and concluding remarks appear in section 6. In this paper, definitions and phrases displayed in the *italic* font are direct quotes from a cited reference (sometimes, additional words are inserted in parentheses to clarify the intended meaning). The proposed terms and definitions are also shown in the *italic* font but underlined to differentiate them from the cited definitions.

2. JCGM 200 concepts, terms, and definitions

We will discuss the JCGM 200 [2] definitions of quantity, quantity value, unit of measurement, measurement standard, measurement, true value of a quantity, uncertainty in measurement, coverage interval, coverage probability, and metrology.

Per JCGM 200 definition 1.1, **quantity** is a *property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference*. In the JCGM 200, property and magnitude are non-defined concepts [2]. A property is a quality (or characteristic) that something has [8]. A property is a feature of anything perceivable or conceivable [9]. A magnitude is size of something [8]. A quantity means an indefinite or a definite amount [8]. So, (a) a property of a phenomenon, body, or substance is a qualitative concept, (b) the magnitude of a property of an individual phenomenon, body, or substance is a quantitative concept, and (c) a quantity is a quantitative concept. For example, mass and length are properties of materials that are distinguished qualitatively. The mass and the length of an individual artifact are magnitudes of properties. The JCGM 200 uses the term quantity for the qualitative concept of a property.

The Note 1 to the JCGM 200 definition of quantity distinguishes 'quantity in a generic (general) sense' from 'quantity of an individual phenomenon, body, or substance' and illustrates that distinction with examples. Examples of a generic quantity include length, energy, and electric charge [2]. These are properties of a phenomenon, body, or substance. Examples of an individual quantity include the radius r_A of a circle A, the kinetic energy T_i of a particle i in a given system, and the electric charge e of the proton [2]. The 'radius r_A of a circle A' is the size of a property called length. The 'kinetic energy T_i of particle i in a given system' is the greatness of a property called energy. The 'electric charge e of the proton' is the magnitude of a property called electric charge. Thus, in the JCGM 200, a generic quantity is a property, and an individual quantity is the magnitude of a property (of an individual phenomenon, body, or substance).

The JCGM 200 definition of quantity has mixed two different concepts: (a) a property (of a phenomenon, body, or substance) which is a qualitative concept, and (b) the magnitude of a property (of an individual phenomenon, body, or substance) which is a quantitative concept. The JCGM is not solely responsible for this mixed-up definition of quantity. Behind it is a long and unfortunate history of various disparate interpretations of the earlier related concepts and terms in English, French, and German [10]. The JCGM has the option of not remaining fettered to the unfortunate history. Separate terms for the concepts of (a) a property and (b) the magnitude of a property will enable more precise vocabulary for metrology.

Per JCGM 200 definition 1.19, **quantity value (value of a quantity)** is a *number and reference together expressing magnitude of a quantity*. Note that in the phrase, **value of a quantity** the word quantity refers to a magnitude, whereas in the phrase, *magnitude of a quantity* the word quantity refers to a property. Thus, one word 'quantity' is used for two different concepts in the same sentence. This is an example of the difficulty that arises from defining quantity to mean both (a) a property and (b) the magnitude of a property. The JCGM 200 definition of quantity value (value of a quantity) can be made clearer by replacing the last word *quantity* with 'property of an individual phenomenon, body, or substance'.

A number and reference together express a definite magnitude of a property. For example, 0 °C (degree Celsius) represents one specific thermodynamic temperature (that specific temperature is a definite magnitude). However, a definite magnitude can be expressed in more than one way, depending on the choice of reference. For example, 0 °C can also be expressed as 32 °F (degree Fahrenheit). Likewise, 3 m (meter) and 300 cm (centimeter) are two different expressions. But they express one specific length (that specific length is a definite magnitude). Thus, a definite magnitude of a property, and an expression for that magnitude are two different concepts. The JCGM 200 definition of a quantity value has mixed these two concepts. For clarity, separate terms are needed for (a) a definite magnitude and (b) an expression for a definite magnitude [10].

Per JCGM 200 definition 1.9, **unit of measurement** is *a real scalar quantity, defined and adopted by convention, with which any other quantity of the same kind can be compared to express the ratio of the two quantities as a number*. This definition is not clear because the meaning of the phrase *real scalar quantity* is not explained. The fundamental problem, however, is that the JCGM 200 definition of the term unit of measurement does not represent the current SI units (see, section 3). The JCGM definition of the term unit needs to be redefined to capture the SI units.

Per JCGM 200 definition 5.1, **measurement standard** is a *realization of the definition of a given quantity, with stated quantity value and associated measurement uncertainty, used as a reference*. A measurement standard is conceptually an intermediary for the traceability of a result of measurement to a reference, not the reference itself. So, the JCGM definition of measurement standard needs to be corrected.

Per JCGM 200 definition 2.1, **measurement** is *process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity*. The Note 2 to this definition states the following: *Measurement implies comparison of quantities or counting of entities*. Per JCGM 200 definition 2.9, a value obtained by measurement is referred to as a *measured quantity value*. The JCGM 200 definition of measurement does not explain that, at its core, measurement is a comparison of an individual quantity with a measurement standard to assign a measured quantity value to that quantity.

Counting is the process of determining the number of entities present in a finite set by assigning the labels 1, 2, …, n to the entities. The largest label n is the number of entities present. Not all counting is measurement. Think of coin counting machines used in banks. Determining the number of entities present in a finite set is not measurement when it is practical indeed to (a) identify the entities to be counted, and (b) counting the identified entities, both without uncertainty. So, the JCGM definition of measurement can be improved.

Per JCGM 200 definition 2.11, **true quantity value (true value of a quantity)** is a *quantity value consistent with the definition of a quantity*. Here, the word *quantity* refers to magnitude. The Note 1 to the JCGM 200 definition 2.11 states that '…, *there is not a single true quantity value but rather a set of true quantity values …, this set of values is, in principle and in practice, unknowable. Other approaches dispense altogether with the concept of true quantity value and rely on the concept of metrological compatibility of measurement results for assessing their validity*.' This JCGM 200 statement wrongly suggests that the concept of a *true quantity value* is analogous to the concept of *metrological compatibility* ([2], section 2.47). Since a true quantity value is unknowable, it cannot be a basis for assessing the validity of a measurement result.

The JCGM 200 states that, '*A reference quantity value can be a true quantity value of a measurand, in which case it is unknown*…' ([2], section 5.18 Note 1). The conceptual idea of an 'unknowable true value of a quantity' cannot serve as a reference value.

Per the GUM, **uncertainty in measurement** is a *parameter, …, that characterizes the dispersion of the values that could reasonably be attributed to the measurand* ([5], section B.2.18). The JCGM 200 echoes the GUM definition as follows: **measurement uncertainty** is a *non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used* ([2], section 2.26). The signal contribution of the GUM is the concept of uncertainty in measurement. The GUM explicitly states, seven times, that the uncertainty in measurement is disconnected from the ideas of true value and error [11].

The JCGM 200 and the JCGM 101 [12] have restored an essentially pre-GUM view of the uncertainty in measurement from the VIM1 [3] and called it a coverage interval with a stated coverage probability. The JCGM 200 definition of a coverage interval refers to 'the set of true quantity values'. The JCGM 101 definition of a coverage interval refers to 'the unique true value of a quantity' but the essential adjectives 'unique' and 'true' are suppressed. The JCGM idea of a coverage interval reconnects, in direct conflict with the GUM, measurement uncertainty and a conceptual true value of a quantity [11].

The JCGM 101 claims that its concept of a coverage interval with a stated coverage probability is based on Bayesian statistical inference ([12], sections 3.12, 5.1.2, and 6.4.9.4 Note 2). The JCGM 200 and the JCGM 101 definitions of a coverage interval with a stated coverage probability are based on the description of a probability density function (PDF) given in the JCGM 104 ([13], section 3.17). Per JCGM 104, *The true values of the input quantities X_1, …, X_N are unknown. In the approach advocated (in the GUM and the JCGM 101) X_1, …, X_N are characterized by (univariate) probability distributions and treated mathematically as random variables. These distributions describe the respective probabilities of their true values lying in different intervals, and are assigned based on available knowledge concerning X_1, …, X_N*. In Bayesian inference for metrology, a PDF expresses the state of knowledge about a fixed quantity (the magnitude of a property). The JCGM 104 is propagating a widespread misunderstanding that in Bayesian inference for metrology the true values of quantities are *treated mathematically as random variables* [14].

The correct JCGM 200 and JCGM 101 interpretation of a PDF is as follows: a PDF describes the state of knowledge about the true value $\tau[Y]$ of a measurand Y. Thus, given an arbitrary possible quantity value y_1 for a measurand Y, a PDF describes the probability that an infinitesimal interval about y_1 contains the true value $\tau[Y]$ of the measurand [14]. The JCGM 200 and the JCGM 101 ideas of a coverage interval with a stated coverage probability are based on this interpretation of a PDF.

Per JCGM 200 definition 2.36, a **coverage interval** is an *interval containing the set of true quantity values of a measurand with a stated probability, based on the information available*. Per JCGM 200 definition 2.37, a **coverage probability** is *probability that the set of true quantity values of a measurand is contained within a specified coverage interval*.

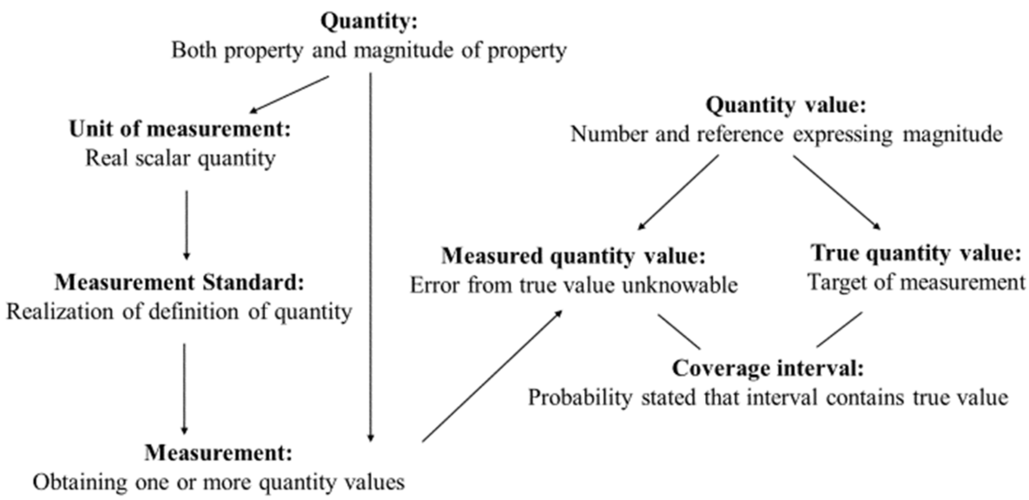

Figure 1. Relationships among the JCGM 200 concepts and terms.

The JCGM 200 idea of a coverage interval with a stated coverage probability is intended as an expression of measurement uncertainty for an ordinary measurand that has a set of true quantity values. Suppose the set of true quantity values of a measurand Y is the fixed but unknowable interval ($\tau_l[Y]$, $\tau_h[Y]$) of width $\tau_h[Y] - \tau_l[Y]$, where $\tau_l[Y]$ and $\tau_h[Y]$ are two true quantity values, and $\tau_l[Y] < \tau_h[Y]$. Consider a tiny coverage interval ($y_1 - \delta$, $y_1 + \delta$) about a possible value y_1 and a positive δ. Suppose the width 2δ of the interval ($y_1 - \delta$, $y_1 + \delta$) is smaller than the width $\tau_h[Y] - \tau_l[Y]$ of the interval ($\tau_l[Y]$, $\tau_h[Y]$) of true quantity values. The smaller interval ($y_1 - \delta$, $y_1 + \delta$) cannot contain the larger interval ($\tau_l[Y]$, $\tau_h[Y]$). So, the coverage probability of the tiny interval ($y_1 - \delta$, $y_1 + \delta$) is zero regardless of the PDF that may be assigned for the state of knowledge about the true value $\tau[Y]$ of the measurand. Under any continuous PDF (such as those described in the JCGM 101, section 6.4), the coverage probability of the tiny interval ($y_1 - \delta$, $y_1 + \delta$) is positive. So, the JCGM 200 idea of a coverage interval breaks down for intervals of width smaller than that of the interval ($\tau_l[Y]$, $\tau_h[Y]$) of true quantity values. Thus, the JCGM 200 definitions of a coverage interval and coverage probability are ill-defined.

Per JCGM 101, a **coverage interval** is *an interval containing the value of a quantity with a stated probability, based on the information available* ([12], section 3.12), and the corresponding **coverage probability** is the *probability that the value of a quantity is contained within a specified coverage interval* ([12], section 3.13). The JCGM 101 has used the phrase *the value of a quantity* for 'the unique true value of a quantity'. The adjective 'true' has been suppressed in display of fealty to the GUM recommendation that the adjective 'true' in 'the true value of a quantity' is unnecessary (see, section 4). The adjective 'unique' has been suppressed because the article *the* before *value of a quantity* implies 'the unique true value of a quantity'.

Per the JCGM 200, the term 'value of a quantity' refers not to a conceptual 'true value of a quantity' but to 'a value that may be assigned to a quantity by measurement' (see, section 4). Thus, the JCGM 101 definitions of a coverage interval and coverage probability are ambiguous. The JCGM 101 definitions can be made clear by replacing the phrase *the value of a quantity* with 'the unique true value of a quantity'.

The JCGM 101 definition of a coverage interval requires the quantity to have a unique true value. So, the JCGM 101 idea of a coverage interval does not apply to an ordinary quantity that has a set of true quantity values due to its inherently incomplete description [11].

The JCGM 101 concept, term, and definition of a coverage interval does not exist in the GUM (excluding Annex G, an ill-fitting add-on) or the VIM2. The idea of a coverage interval was introduced by the JCGM 200 and the JCGM 101 in 2008.

The JCGM 101 concept of a coverage interval directly conflicts with the concept of uncertainty in measurement, which is disconnected from the conceptual idea of an unknowable true value.

A term and definition are needed for a result of measurement expressed as an interval (not necessarily symmetric about a specified value) that agrees with the concept of uncertainty in measurement established by the GUM.

Per JCGM 200 definition 2.2, **metrology** is *science of measurement and its application*. More than science, the technology of measurement is the source of many advancements in metrology. The JCGM 200 definition does not include the essential distinguishing features of metrology to (a) establish quantity values, that are recognized throughout the world, (b) enable metrological compatibility of quantity values assigned to a given quantity at various places and times, and (c) establish connections between different expressions of a given quantity value. The JCGM definition of metrology needs to be expanded.

Figure 1 displays the relationships among the JCGM 200 concepts and terms. Note that the JCGM 200 definition of the term unit of measurement does not represent the current SI units. The JCGM 200 and the JCGM 101 have restored an essentially pre-GUM view of the uncertainty in measurement from the 1984 VIM1, which is about stating a subjective probability that a 'coverage interval' contains the unknowable true value of a quantity.

3. Proposed concepts, terms, and definitions

Separate terms for (a) a property which is a qualitative concept, and (b) the magnitude of a property which is a quantitative concept will bring clarity in the vocabulary of metrology. The term 'magnitude' is a noun that refers to the ideas of size, extent, greatness, dimension, weight, degree, intensity, amount, and number. The criterion for comparing individual phenomenon, body, or substance is generally their magnitudes for one or more properties. Thus, the magnitude of a property (of an individual phenomenon, body, or substance) is a fundamental concept in metrology.

In the JCGM, a viewpoint that has gained popularity is to avoid the term magnitude. This is unfortunate. Leading members of the JCGM claim that the term magnitude is difficult to translate in some (unspecified) languages. My attempts to verify this claim have failed. It is inconceivable that adequate translations of the term magnitude do not exist in languages relevant for metrology. As a last resort, the term magnitude can be adopted in other languages.

We refer to the properties (features, attributes, or characteristics) that can have various magnitudes as measurable properties. The adjective 'measurable' for a property is borrowed from the GUM ([5], section B.2.1). We refer to the properties that do not have the concept of magnitude as nominal properties. Presence or absence of the concept of magnitude determines whether a property is measurable or nominal. The JCGM 200 (VIM3) is largely concerned with measurable properties. The JCGM 200 term **kind of quantity** [2] refers to a measurable property.

Measurable property is *a property of a phenomenon, body, or substance that can have various magnitudes*. Examples of a measurable property are length, energy, electric charge, electric resistance, amount-of-substance concentration of an identified entity, number concentration of an identified entity, and the hardness on Rockwell C scale [2]. The phrase '*phenomenon, body, or substance*' has broad meaning, it includes all that exists, facts, occurrences, and circumstances observed or observable in the universe. Phenomenon that arise in a scientific experiment are included. The word '*magnitude*' also has broad meaning, it includes, for example, both amounts and numbers.

Quantity is *the magnitude of a property of an individual phenomenon, body, or substance*. Examples of a quantity are radius of a given circle, wavelength of the sodium D radiation, kinetic energy of an identified particle in a given system, heat of vaporization of a given sample of water, electric charge of the proton, electric resistance of an identified resistor in a given circuit, amount-of-substance concentration of ethanol in a given sample of wine, number concentration of erythrocytes in a given sample of blood, and the hardness of a given sample of steel on Rockwell C scale [2]. The description of a quantity includes specification of the property as well as an individual phenomenon, body, or substance. This definition of quantity is unlikely to be problematic because the term quantity is widely used for the magnitude of a property.

The magnitude of a property (of an individual phenomenon, body, or substance) is indefinite before measurement. The target of measurement is that indefinite magnitude. So, the concept of an indefinite magnitude is advantageous in metrology. We have introduced the term real quantity for an indefinite magnitude of a property. We have retained the term quantity value for a definite magnitude that may be assigned to a real quantity.

Real quantity is *an indefinite magnitude of a property of an individual phenomenon, body, or substance*. A real quantity can change with time and location from interactions of the property with the environment, and from handling of the materials by humans and machines.

Note 3.1: Ordinary and special real quantities

A 'real quantity affecting property' is one whose magnitude affects the real quantity of interest. For example, the real quantity affecting properties for the velocity of sound in dry air include air composition, temperature, and pressure ([5], section D.1.2). Real quantities can be divided into two classes: (a) ordinary real quantities, and (b) special real quantities. An ordinary real quantity is an indefinite magnitude that is specified by its description, including specification of significant real quantity affecting properties. Most real quantities of interest in metrology are ordinary real quantities. Consider the length of a bar of steel. Temperature is a real quantity affecting property. When the temperature is not specified, the bar has a range of lengths corresponding to different temperatures. It is neither practical nor necessary to identify and specify all real quantity affecting properties. Therefore, the description of every ordinary real quantity is necessarily incomplete. Knowingly or unknowingly, a property whose magnitude affects the real quantity is left unspecified. When a real quantity affecting property is left unspecified, the real quantity is a range. Thus, every ordinary real quantity is a range of magnitudes. Paul De Bievre describes some challenges in specifying a chemical quantity intended to be measured [7]. A special real quantity is a unique magnitude. It may arise in a scientific experiment. Fundamental constants of nature and some other technical constants of physics and chemistry are special real quantities. Fundamental and technical constants have unique magnitudes. So, they are unique invariant quantities.

Measurand is *a sufficiently well-described real quantity to which a quantity value is to be assigned*. The phrase *sufficiently well-described real quantity* means that the measurand is described in sufficient detail such that it can be adequately represented (characterized) by an assigned quantity value with an associated standard uncertainty (or by an interval or by a probability distribution of assigned quantity values) [11].

An ordinary measurand is a range of magnitudes because of its necessarily incomplete description. When the component of uncertainty arising from incomplete description of the measurand is significant, it is included in the combined measurement uncertainty ([5], section D.3.4). However, it is important to realize that an indication from a measuring system is typically the output for a single indefinite magnitude that was input in the real-time.

Quantity value is *a definite magnitude that may be assigned to a quantity*. A metrological expression is required to represent a definite magnitude. The term quantity value may be abbreviated as value.

Metrological expression is *a number together with a metrological reference*. A given quantity value may be represented by various metrological expressions, depending on the choice of reference. Thus, for example, $v = 25$ m s^{-1} (meter per second) and $v = 90$ km h^{-1} (kilometer per hour) are two metrological expressions, but they represent one quantity value (a specific speed v). A metrological expression relates to metrology as a number relates to arithmetic. A numerical expression is a number.

Metrological reference is *usually a unit of measurement, but it could be a measurement procedure, a certified reference material (CRM), or a combination of such*. For example, the reference for quantifying the hardness of metal alloys is a measurement procedure. In chemistry, the measurand is often the concentration of a component in a sample of material. The result of measurement strongly depends on the other components and their concentrations in the sample. Complete composition of the sample is typically unknown. So, quantity values assigned to appropriate CRMs are used as a reference for measurement. For example, natural gas CRMs are used to calibrate a gas chromatograph for measuring the calorific value of natural gas. The quantity value of a CRM is sometimes traceable to the appropriate units of measurement.

A quantity value is typically assigned to a real quantity by measurement. In most cases, a result of measurement is obtained through a functional relationship called measurement equation. Corrections and correction factors for the systematic effects included in the measurement equation are regarded as quantities to which quantity values and associated standard uncertainties are assigned from the available information ([5], section 4.1).

A result of measurement may be (a) a single assigned quantity value, (b) a range of quantity values or (c) a probability distribution of quantity values. A result of measurement describes the state of knowledge about a real quantity. A single assigned quantity value is incomplete without measurement uncertainty; nevertheless, it may be adequate for an intended purpose when the associated uncertainty is known to be sufficiently small. After a result of measurement is assigned, the real quantity becomes known up to the stated measurement uncertainty.

Known quantity is *the magnitude of a property of an individual phenomenon, body, or substance to which a quantity value with a stated measurement uncertainty has been assigned*.

An assignment of a quantity value to a real quantity is a unidirectional metrological operation. In metrology, the distinction between a 'metrological assignment' and an 'equality' is very important. If b is a quantity value assigned to a real quantity a, and the arrow '$\leftarrow$' represents a 'metrological assignment' then we may write $a \leftarrow b$. Typically, the left side of a metrological assignment, represented by an arrow '$\leftarrow$', is a real quantity and the right side is a result of measurement assigned to that quantity. The equal sign ' $=$ ' represents equality; that is, no difference. If $a = b$, then a and b have the same worth, value, and function, one could replace the other.

An indefinite magnitude a cannot be numerically subtracted from a definite magnitude b assigned to it. Thus, the separation between a real quantity (indefinite magnitude) and a quantity value (definite magnitude) assigned to that real quantity is qualitative. The concept of uncertainty in measurement established by the GUM does not refer to this qualitative gap. However, measurement uncertainty includes components of uncertainty associated with the random effects and the corrections applied for all recognized significant systematic effects ([5], section 3.3.1).

3.1. A brief introduction to the current SI system of units

The most important system of the units of measurement is the International System of Units, called the SI. The current ninth edition of the SI Brochure has established new definitions for the SI base units and the other SI units by fixing the numerical values for a chosen set of fundamental or technical constants of nature referred to as the defining constants [15]. Barry Taylor has described the quantity calculus used to derive the new SI base units [16].

In the SI, a metrological expression for a quantity value Q is a product of a number $\{Q\}$ and a unit of measurement $[Q]$; that is, $Q = \{Q\}\ [Q]$. The names of the SI units of measurement for the length and the mass of an individual artifact are meter and kilogram, with symbols m and kg, respectively. The corresponding symbols for the units are 1 m and 1 kg, respectively. The quantity value 'three kilograms' for example is commonly expressed as 3 kg. The expression 3 kg is an abbreviation for the metrological expression {3} [1 kg]. Symbols such as m, kg, and s are referred to as unit symbols. Per Barry Taylor, '*In the quantity calculus, unit symbols are treated as normal algebraic quantities.*' [16]. Thus, $1\ x = x$, where x is a unit symbol, and an SI quantity value Q is an algebraic variable. The symbols like 1 m, 1 kg, and 1 s are preferred for the units. An SI unit symbol (for example, m, kg, and s) preceded by a number is a metrological expression. A unit of measurement could be the number 'one'. In that case the quantity value Q is a number $\{Q\}$.

The base units of the SI are still second, meter, kilogram, ampere, kelvin, mole, and candela. Seven defining constants were chosen to redefine the base units. The 'best-known' quantity values using the previous SI units were assigned to the defining constants. The measurement uncertainties associated with the assigned quantity values were zeroed. The zeroing of the uncertainties means that the quantity values assigned to the defining constants are fixed and established (rather than results of measurement). Then the established quantity values were used to redefine the SI units for the defining constants [16]. Next, the SI units for the defining constants were used to redefine the base units of the SI. Per the SI Brochure, *The set of seven defining constants has been chosen to provide a fundamental, stable and universal reference that simultaneously allows for practical realizations with the smallest uncertainties* [15].

The zeroing of measurement uncertainties associated with the quantity values assigned to the defining constants

Table 1. The seven defining constants of the SI and the seven corresponding units they define.

Defining constant	Symbol	Numerical value	Unit
Hyperfine transition frequency of Cs	$\Delta\nu_{Cs}$	9 192 631 770	Hz
Speed of light in vacuum	c	299 792 458	m s^{-1}
Planck constant	h	$6.626\ 070\ 15 \times 10^{-34}$	J s
Elementary charge	e	$1.602\ 176\ 634 \times 10^{-19}$	C
Boltzmann constant	k	$1.380\ 649 \times 10^{-23}$	J K^{-1}
Avogadro constant	N_A	$6.022\ 140\ 76 \times 10^{23}$	mol^{-1}
Luminous efficacy	K_{cd}	683	lm W^{-1}

translates into positive uncertainties for some of the previous SI units. Thus, in the revised SI, the mass of the international prototype of kilogram (IPK) has quantity value 1 kg with a relative standard uncertainty of 1×10^{-8}. The molar mass of carbon 12, $M(^{12}C)$ has quantity value 0.012 kg mol^{-1} with a relative standard uncertainty of 4.5×10^{-10}. The triple point of water, T_{TPW}, has quantity value 273.16 K with a relative standard uncertainty of 3.7×10^{-7} [15].

Table 1 is reproduced from the ninth edition of the SI brochure [15]. We will use table 1 to exemplify the following concepts and terms: real quantity, quantity value, metrological expression, known quantity, and the SI units of measurement. We will also describe the interpretation of table 1 as given in the SI Brochure.

The names of the defining constants listed in column 1 identify real quantities for which quantity values have been established; hence, they identify known quantities. The symbols $\Delta\nu_{Cs}$, c, h, e, k, N_A, and K_{cd} listed in column 2 denote the quantity values established for the defining constants. The entries in column 4 are unit symbols. The products of the numerical values in column 3 and the corresponding unit symbols are metrological expressions for the quantity values listed in column 2. Thus, $\Delta\nu_{Cs} = 9\ 192\ 631\ 770$ Hz, $c = 299\ 792\ 458$ m s^{-1}, $h = 6.626\ 070\ 15 \times 10^{-34}$ J s, $e = 1.602\ 176\ 634 \times 10^{-19}$ C, $k = 1.380\ 649 \times 10^{-23}$ J K^{-1}, $N_A = 6.022\ 140\ 76 \times 10^{23}$ mol^{-1}, and $K_{cd} = 683$ lm W^{-1}. The symbols Hz, J, C, lm, and W, represent the units of measurement hertz, joule, coulomb, lumen, and watt, respectively. The units of the quantity values listed in table 1 are related to the SI base units second, meter, kilogram, ampere, kelvin, mole, and candela, with unit symbols s, m, kg, A, K, mol, and cd, respectively, according to 1 Hz = 1 s^{-1}, 1 J = 1 kg m^2 s^{-2}, 1 C = 1 A s, 1 lm = 1 cd m^2 m^{-2}, and 1 W = 1 kg m^2 s^{-3}, respectively. The seven metrological expressions were solved for the seven SI base unit symbols s, m, kg, A, K, mol, and cd. The result is seven algebraic equations for the SI base unit symbols ([16], (8a), (8b), …, (8 g)). For example, the algebraic equations for the first three of the seven SI base units (for time, length, and mass) are as follows:

$$1\ \text{s} = 9\ 192\ 631\ 770 \frac{1}{\Delta\nu_{Cs}}, \tag{1}$$

$$1\ \text{m} = \frac{9\ 192\ 631\ 770}{299\ 792\ 458} \frac{c}{\Delta\nu_{Cs}}, \tag{2}$$

$$1\ \text{kg} = \frac{(299\ 792\ 458)^2}{(6.626\ 070\ 15 \times 10^{-34})\ (9\ 192\ 631\ 770\ )} \frac{h\Delta\nu_{Cs}}{c^2}. \tag{3}$$

If the metrological expressions for the quantity values $\Delta\nu_{Cs}$, c, and h are substituted in the right sides, then (as expected) these equations reduce to 1 s = 1 s, 1 m = 1 m, and 1 kg = 1 kg, a tautology. However, when the symbols $\Delta\nu_{Cs}$, c, h, e, k, N_A, and K_{cd} are regarded not as denoting the quantity values but as symbols for the defining constants (quantities) themselves, the seven algebraic equations such as equations (1)–(3) become the definitions of the SI base units stated in the SI Brochure [15].

In the SI Brochure, the symbols $\Delta\nu_{Cs}$, c, h, e, k, N_A, and K_{cd} are used for the defining constants (quantities) themselves [15]. In the algebra used to derive the definitions of the SI base units, the symbols $\Delta\nu_{Cs}$, c, h, e, k, N_A, and K_{cd} are regarded as algebraic variables with assigned values $\Delta\nu_{Cs} = 9\ 192\ 631\ 770$ Hz, $c = 299\ 792\ 458$ m s^{-1}, $h = 6.626\ 070\ 15 \times 10^{-34}$ J s, $e = 1.602\ 176\ 634 \times 10^{-19}$ C, $k = 1.380\ 649 \times 10^{-23}$ J K^{-1}, $N_A = 6.022\ 140\ 76 \times 10^{23}$ mol^{-1}, and $K_{cd} = 683$ lm W^{-1}. The seven assigned values are metrological expressions for the quantity values assigned to (established for) the defining constants (quantities). The symbol ‘ = ’ between the left side and the right side is for ‘equality’ not for ‘metrological assignment’ (for which one could use, for example, the arrow ‘←’). Thus, in the SI Brochure, the symbols $\Delta\nu_{Cs}$, c, h, e, k, N_A, and K_{cd} are used for both the defining constants (quantities) and the corresponding assigned quantity values [15, 16].

The SI Brochure [15] includes two viewpoints on the definition of the term unit of measurement: (a) a stated definition, and (b) descriptions of the current SI base units. We will discuss both viewpoints. The SI Brochure defines the term unit of measurement as follows.

Unit of measurement: *The value of a quantity is generally expressed as the product of a number and a unit. The unit is simply a particular example of the quantity concerned which is used as a reference, and the number is the ratio of the value of the quantity to the unit* ([15], section 2.1). This definition states that a unit is a physical quantity which is used as a reference. Here, the concepts of a unit of measurement and its physical realization are one and the same.

The definition of the term unit is expected to capture the current SI units. Concerning the current SI units, the SI Brochure states that, ‘*Here, the realizations are separated conceptually from the definitions so that the units can, as a matter of principle, be realized independently at any place and at any* *time*' ([15], section 1.2). Thus, an SI unit of measurement is now conceptually separate from its physical realization. Such is not the case in the definition of the term unit stated in the SI Brochure ([15], section 2.1).

In the SI Brochure, the seven algebraic equations for the SI base units 1 s, 1 m, 1 kg, 1 A, 1 K, 1 mol, and 1 cd, like the equations (1)–(3), are complete descriptions of the SI base units. Thus, for example, equation (3) is a complete description of the unit of mass, 1 kg, where $\Delta\nu_{\mathrm{Cs}}$ is the hyperfine transition frequency of the cesium 133 atom, c is the speed of light in vacuum, and h is the Planck constant. Thus, an SI unit of measurement is a definition within a system of units. In the current SI, the units (definitions) and their physical realizations (implementations of the definitions) are conceptually separate. The SI is setup such that the physical realizations of the units embody the quantities concerned.

The current concept of a unit of measurement has the following three characteristics. (a) A unit is a definition, within a system, which is used as a metrological reference. (b) The current SI (system of units) was developed by establishing fixed quantity values for a chosen set of seven unique invariant quantities (defining constants). (c) A unit is realizable physically in a practical form embodying the quantity concerned. A physical realization of a unit serves as a measurement standard. A unit of measurement has no uncertainty because it is a definition, but its physical realization carries uncertainty. The SI is a coherent system.

The seven chosen 'unique invariant quantities' for the SI are so from the viewpoint of our (human) current understanding of nature (universe). In principle, the set of unique invariant quantities used to establish the SI is modifiable or expandable. The following definition of the term unit captures the current SI units.

Unit of measurement is *a definition which is used as a reference to assign a value to a quantity by comparing it with a physical realization of that definition*. Outside of the SI, ad hoc units of measurement may be constructed where a unit and its physical realization are identical.

König [17] and Silsbee [18] expounded the two views of measurement referred to as the Realist and the Synthetiker. Briefly, a realist is an experimentalist who deals with concrete physical quantities, measurement standards, and physical laws having concrete interpretations of nature. A Synthetiker is a theoretician who develops and uses abstract concepts and models to describe the materials and phenomena in nature. Measurements bind the scientific models to the concrete physical reality [17–19].

The definition of the term unit in the SI Brochure is a Realist view. However, the definitions of the SI base units in the SI Brochure are Synthetiker view.

The terms and definitions proposed in this article define abstract concepts. Abstract concepts such as these serve as elements for the scientific models of phenomena that happen in nature.

Note 3.2: Is a unit of measurement a quantity or a quantity value?

This question is sometimes asked for the following reason. (a) Measurement, at its core, is a comparison of two quantities of which one has a declared value. So, the earliest units of measurement were physical quantities. Until recently (2019), the SI unit of mass was the mass of an artifact, a quantity. (b) In the SI, a quantity value Q is expressed as a product of a number $\{Q\}$ and a unit [Q]; that is, $Q = \{Q\}\ [Q]$, where $\{Q\} > 0$. Algebraically, $[Q] = \{Q\}^{-1}\,Q$. In the special case $\{Q\} = 1$, the unit $[Q] = Q$, a quantity value. A quantity value Q can be used as a unit $[Q]$ only when it is tied to (established for) a suitable physical quantity. The criteria for a suitable physical quantity include its usability in assigning values to like quantities by comparison.

Now (in view of the ninth edition of the SI), a unit of measurement is a definition which is used as a reference, and a physical realization of the unit embodies the quantity concerned. A unit (definition) and its physical realization (implementation of the definition) are paired concepts (because a definition that is not realizable in a practical form is of no use). The SI units (definitions) are based on both the quantities (defining constants) and the quantity values established for the defining constants. Mathematically, an SI unit may be regarded as an output of a function, the inputs are the defining constants (quantities), and the function is specified by the quantity values established for the defining constants.

Measurement standard is *usually a physical realization of a unit, with a stated quantity value and associated measurement uncertainty, but it could be an implementation of a measurement procedure or a CRM*. Measurement standards are designed and developed to link a result of measurement with a metrological reference. Measurement standards for a unit of measurement are hierarchical. Lower-level standards are calibrated against higher-level standards. At the top of hierarchy are primary standards. A primary standard is a physical realization of a unit of measurement. Typically, a CRM is both a reference and a measurement standard.

Measurement is a foundation of most human enterprises such as science, technology, healthcare, agriculture, commerce, and law enforcement. The details of measurement are as varied as the application areas. The key characteristic of a measurement is as follows.

Measurement at its core is *a process of comparing a real quantity (the measurand or a close approximation, or a related quantity) with an appropriate measurement standard to assign the real quantity one or more quantity values that are traceable to a unit of measurement or another reference. Sometimes a quantity value is assigned by a measurement procedure used as reference*. The comparison of a quantity with a measurement standard may be implicit in a measuring instrument or a measuring system. To assign a result of measurement to the measurand, many indirect and intricate measurement procedures may be required [5]. Typically, a result of measurement is determined from the values and uncertainties assigned to various quantities through a measurement equation ([5], section 4.1). A measurement equation is developed by inverting the model of measurement. Modeling of the measurement is the most critical part of uncertainty analysis.

Measurement includes determining the number of entities (such as atoms and molecules) present in a chemical system or the number events (such as radioactive decays and failures) that occurred during a specified period. The quantity is the number of entities present or the number of events that occurred. A quantity value is a number assigned to the quantity of interest. Usually, such a measurement consists of two processes: (a) identifying the entities (or detecting the events) to be counted, and (b) determining the number of entities present (or the number of events that occurred) by counting or by some other more practical method. Typically, both processes carry uncertainty. Thus, counting may be a part of some measurements. A measurement carries uncertainty. Elementary counting without uncertainty is not measurement.

Sometimes it is necessary to express a result of measurement as an interval. In the GUM, when it is necessary to express a result of measurement for a measurand Y as an interval, it is expressed as $(y \pm k{\cdot}u(y))$, where y is a specified (central) quantity value with standard uncertainty $u(y)$ and k is a specified multiple called coverage factor. The interval $(y \pm k{\cdot}u(y))$ is referred to as a ***k*-standard uncertainty interval or an expanded uncertainty interval**. Usually, k is 1 or 2, but not greater than 3. The interval $(y \pm k{\cdot}u(y))$ consists of a large fraction of the distribution of quantity values that could be attributed (assigned) to the measurand Y. The GUM refers to the fraction of the distribution of quantity values covered by the interval $(y \pm k{\cdot}u(y))$ as **coverage probability** ([5], sections 2.3.5 and 6.2.1).

A result of measurement more general than the interval $(y \pm k{\cdot}u(y))$ is the interval (y_l, y_h), where y_l and y_h are two chosen quantity values and $y_l < y_h$. The GUM left a gap by not mentioning the more general interval. In the reference [14], I proposed the term interval result for the more general interval (y_l, y_h). To associate a coverage probability with an interval result (y_l, y_h), a PDF is required for the quantity values that could be attributed to the measurand Y. In the essential GUM (excluding Annex G), such a PDF describes the probability with which an arbitrary possible quantity value y_1 could be attributed to the measurand Y [11, 14]. The probability associated with a quantity value y_1 is the probability under the PDF of an infinitesimal interval about y_1.

Interval result is *a range of quantity values that with varying degrees of credibility could be attributed to the measurand based on the information, model, and assumptions used*. The degree of credibility is generally expressed as a probability. The term 'interval result' is an abbreviation for 'a result of measurement expressed as an interval'.

Coverage probability *associated with an interval result is the probability with which the quantity values in that interval could be attributed to the measurand*. Thus, the coverage probability of an interval result (y_l, y_h) is the fraction of a PDF over the possible quantity values for the measurand Y covered by the interval (y_l, y_h) ([5], sections 2.3.5 and 6.2.1). The proposed definitions of an interval result and its associated coverage probability agree with the concept of measurement uncertainty established by the essential GUM (excluding Annex G) as well as Bayesian statistical inference for metrology [11, 14].

The following definition is an attempt to capture the essential features of metrology.

Metrology is *the science and technology of measurement at all levels of uncertainty to (a) establish metrological expressions for a quantity value that are recognized and accepted throughout the world, (b) make it practical for different quantity values assigned to a given real quantity at various places and times to be metrologically compatible up to the stated measurement uncertainties, and (c) establish connections between different metrological expressions for the same quantity value*. Metrology is usually divided into three subfields: (a) scientific metrology, (b) industrial metrology, and (c) legal metrology.

Scientific metrology deals with establishing units of measurement, developing measurement standards and measuring techniques, enabling traceability chains from the units of measurement (and other references) to the results of measurement, and demonstrating mutual recognition and agreements of measuring techniques and measurement standards at various level of the traceability chains. Uncertainty analysis is a key element of scientific metrology.

Industrial metrology is concerned with the application of measurement science and technology to manufacturing, trade, commerce and other such processes, and their use in society, ensuring the suitability of measuring instruments, their calibration, and quality control of measurements.

Legal metrology is concerned with regulatory requirements of measuring instruments and measurements for the protection of the environment, protection of consumers, fair trade, enabling taxation, public safety, healthcare, and law enforcement.

The world of measurements for healthcare and pharmacology has all three components: scientific, industrial, and legal metrology. Measurements in pharmacology are often not based on the SI because of many practical difficulties.

In scientific metrology, a result of measurement must include uncertainty in measurement. In industrial metrology, a result of measurement is often a single quantity value assigned by a measuring instrument (system) whose 'maximum permissible deviation with respect to a measurement standard' is known.

The uncertainty approach is widely used in scientific metrology. Adaptation of the uncertainty approach for industrial and legal metrology is a largely unexplored area for research and application.

Figure 2 displays the relationships among the proposed concepts and terms. Note that the proposed definition of the term unit of measurement represents the current SI units. A given quantity value may have many metrological expressions depending on the choice of unit. The uncertainty in measurement is disconnected from the concept of an unknowable true value of the measurand. Figures 1 and 2 display different understandings of the core concepts in metrology.

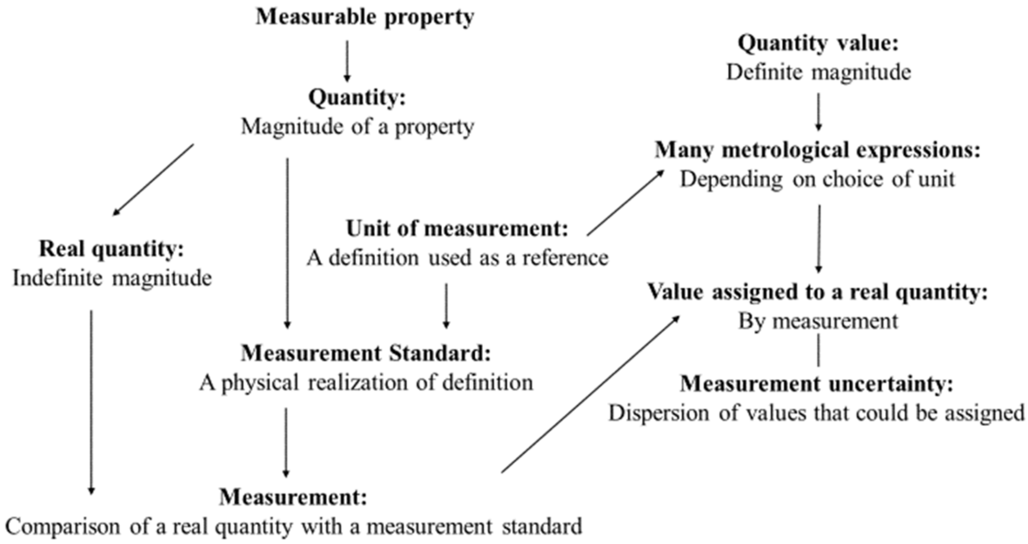

Figure 2. Relationships among the proposed concepts and terms.

4. Real quantity versus true value of a quantity as the target of measurement

According to the JCGM 200, '*In the GUM, the concept of true value is kept for describing the objective (target) of measurement, but the adjective "true" is considered to be redundant*'. Caveat: the uncertainty in measurement is disconnected from a conceptual true value.

Per the GUM ([5], section B.2.3), **true value (of a quantity)** is a *value consistent with the definition of a given particular quantity. This (true value of a quantity) is a value that would be obtained by a perfect measurement* ([5], section B.2.3 Note 1). Per the GUM ([5], section D.3.5), *…the word 'true' is viewed as redundant*. Why is the word 'true' in 'true value' redundant?

According to the GUM ([5], section D.3.5), once a quantity is specified it has a fixed conceptual value. That conceptual value is referred to as a true value. (Depending on the degree of detail to which the quantity is specified, it has a range of true values ([5], section D.3.4).) A true value is imagined to be an inherent attribute of the specified quantity. Per the GUM, the adjective 'true' in 'true value of a quantity' is a duplication of the statememt that since the quantity is already specified, its concptual value is fixed. Thus, according to the GUM, the adjective 'true' in 'true value of a quantity' is unnecessary ([5], section D.3.5). So, the GUM recommends the term 'value of a quantity' instead of the term 'true value of a quantity' for the same concept. This clarification of the viewpoint of GUM does not exist in any JCGM document.

Per the JCGM 200 definitions 1.19 and 2.1, the terms 'quantity value' and 'value of a quantity' are synonyms which refer to a value that may be assigned to a quantity by measurement. Per the JCGM 200, the term 'true value of a quantity' is a designation for the target of measurement [2]. Thus, the GUM recommendation of suppressing the adjective 'true' from a 'true value of a quantity' has the effect of confounding the JCGM term for 'the target of measurement' with a term for 'a value that may be assigned to a quantity by measurement'. So, this recommendation in the GUM is problematic. Despite that, in introducing the idea of a coverage interval, the JCGM 101 followed this recommendation.

I think that a quantity does not have a value until a value is assigned to it by measurement (or established for it by definition). A value assigned to a quantity is a human invention (an abstract idea) that has made the science and technology possible. Before measurement, all one has is an indefinite magnitude of a property (of an individual phenomenon, body, or substance) for which we have proposed the term real quantity. Thus, a real quantity is a better concept for the target of measurement than an imaginary true value of a quantity.

5. Summary

(a) The JCGM 200 definition of quantity has mixed two different concepts: (1) a property (of a phenomenon, body, or substance) which is a qualitative concept, and (2) the magnitude of a property (of an individual phenomenon, body, or substance) which is a quantitative concept. We introduced the concept of a measurable property and retained the term quantity for the magnitude of a property.

(b) The magnitude of a property is indefinite before measurement. The target of measurement is that indefinite magnitude. So, the concept of an indefinite magnitude is advantageous in metrology. The JCGM 200 has ignored this concept. Therefore, we introduced the term real quantity for an indefinite magnitude of a property (of an individual phenomenon, body, or substance).

(c) We retained the term quantity value for a definite magnitude that may be assigned to a real quantity. After a quantity value and measurement uncertainty are assigned, the real quantity becomes known up to the stated measurement uncertainty. We introduced the term known quantity for the magnitude of a property to which a quantity value and measurement uncertainty have been assigned.

(d) The JCGM 200 definition of a quantity value has mixed two different concepts: (1) a definite magnitude and (2) an expression for a definite magnitude. We introduced the term metrological expression for a number together with a metrological reference. A given quantity value may be represented by many equivalent metrological expressions.

(e) The JCGM 200 definition of the term unit of measurement does not represent the current SI units. So, we introduced a new definition of the term unit. A unit of measurement is a definition which is used as a reference. A physical realization of the unit embodies the quantity concerned.

(f) We corrected the JCGM 200 definition of a measurement standard. A measurement standard is an intermediary for the traceability of a result of measurement to a metrological reference, not the reference itself.

(g) We revised the JCGM 200 definition of measurement. At its core, a measurement is a comparison of a real quantity with a measurement standard to assign a value to that real quantity.

(h) The JCGM 200 (and the JCGM 101) idea of a coverage interval directly conflicts with the concept of uncertainty in measurement established by the GUM. We introduced and defined the term interval result (for a result of measurement expressed as an interval) that agrees with the concept of uncertainty in measurement.

(i) We expanded the JCGM 200 definition of metrology to include its essential features.

(j) We promulgated the idea that a real quantity (indefinite magnitude of a property) is a better concept for the target of measurement than an imaginary true value of a quantity.

6. Concluding remarks

(a) The reason for existence of a technical vocabulary is to clarify concepts and dispel confusion. Carefully developed concepts, terms and definitions improve understanding, practice, and communication. This study of a sample of ten definitions suggests that the JCGM may wish to consider doing a major revision of the five chapters of JCGM 200.

(b) The JCGM has a good plan to consolidate the concepts and terms relating to nominal properties in a separate chapter. For example, the JCGM 200 definition 5.13 of 'reference material' is awkward because it has mixed the concepts for measurable properties and nominal properties.

(c) Scales of measurement are categorized into nominal, ordinal, interval, and ratio, where ratio scale is the most informative and nominal the least [20]. Quantity values expressed in the SI units are measurements on a ratio scale. Some quantity values are expressed on an ordinal scale ([2], sections 1.26 and 1.28) because of convenience and the current state of measurement science and technology. Two common examples are hardness of metal alloys, and octane ratings of petroleum fuels. In view of the Representational Theory of Measurement (RTM), only ratio scales are quantitative [19]. Ordinal scales are operational. So, separate chapters for measurements (1) on a ratio scale, and (2) on an ordinal scale would make the concepts in metrology more precise. In addition, a separate chapter for CRMs would make the terms and definitions clearer.

(d) The JCGM 200 has mixed the concepts, terms, and definitions for (1) the pre-GUM true value approach, and (2) the uncertainty approach ([2], Introduction). This mixture led to undermining the concept of uncertainty in measurement established by the GUM [11, 14]. So, it would be better to have separate chapters for (1) the uncertainty approach, and another chapter if needed for (2) the pre-GUM true value approach.

Data availability statement

No new data were created or analysed in this study.

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Disclaimer

This research paper reflects only the views of the author on the topics discussed and does not necessarily reflect the official position that his employer, NIST, may have about these topics or about the GUM, the JCGM documents, and the BIPM-CIPM documents.

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