

From Giovanni Giorgi's Metrological Proposal to Standards Series ISO/IEC 80.000, Quantities and Units

Hans Teichmann

Lausanne, Switzerland
teichmann.hans@bluewin.ch

Abstract

In all fields of scientific/technical activity and in all countries, the SI (Système international d'unités - International System of Units) is nowadays recognized and well understood. The Italian engineer and scientist Giovanni Giorgi presented in 1901 for the first time his revolutionary metrological proposal. The present study considers the background of the SI and the subsequent development of the SI-based joint, harmonized International Standards Series ISO/IEC 80.000: Quantities and Units. It covers in principle all relevant technical specialties and is undergoing continued development in two responsible Technical Committees, ISO/TC 12 respectively IEC/TC 25, and in ITU-T's Study Group (SG) 17.

As the SI is a living system, it shall reflect current best measurement practice. In November 2018, the "Bureau international des poids et mesures (BIPM)" therefore decided to redefine fundamentally the world's current measurement system, which will from now on be based exclusively on unchanging, fundamental properties of nature. It is important that the four revised SI base units (kilogram, ampere, kelvin and mole) did not change in value.

The USA is currently the only industrialized country, which is still using its traditional non-metric system, the "U.S. Customary measures". The underlying reasons and resulting practical implications are considered.

1 Introduction

Most people are blissfully unaware of the enormous number of precision measurements that make modern life possible. For example, every component of a smartphone – its processing chip, memory, microphone and camera optics – depends on an infrastructure of meticulously measured and tested scientific principles, materials, tools and processes. They combine to ensure that the phone can reliably make calls, send texts, access to internet and use GPS. Such measurements virtually make the world go round (NIST, 2018b). This worldwide measurement infrastructure grew out of the original French system, which was conceived in 1790 with units ultimately based on nature itself: The kilogram was the mass of one liter of water, and the meter was defined as one ten-millionth of the distance from the North pole to the equator. Those units, however, had to be embodied in physical objects, such as the meter bar and a piece of metal that serves as the kilogram. But these objects could actually wear out.

In most countries of the world, the standards of International Organization for Standardization (ISO) and of the International Electrotechnical Commission (IEC) are now adopted as national standards. But the idea of applying decimal fractions to weight and measures is not a recent one: Decimal systems have been created and debated by savants in England, France and Italy already starting in the 1660s (Marciano, 2014). In the age of the French

Revolution, in all European and overseas countries a virtually uncountable number of measures still were used. Leading French scholars and radical revolutionaries were convinced that all measures needed to be decimalized. These advocates of decimalization even suggested – albeit without lasting success – the introduction of decimal systems for somewhat odd fields like the clock, calendar and geographical degrees.

They were also convinced that France must not just be incrementally improved, but it should represent the very model of enlightened progress and a shining beacon for all mankind. Scientific standards would then no longer be arbitrary, but derived from a higher authority, namely nature itself. The new system of measures would help unite not only France, but the world as a whole. And this system was supposed to be “for all times, for all peoples”.

The present paper will shed some light at the legacy of the Italian scientist and engineer Giovanni Giorgi who proposed a trailblazing, coherent system of four base units, and at the complicated, almost dramatic historic background of the SI. The study will then put into perspective the crucial role of physical quantities and units in modern science and technology. It will also show why global standardization is a never-ending task: Competent bodies in ISO, IEC and ITU-T have now completed the harmonization of the joint fundamental Standards Series ISO/IEC 80.000 on physical quantities and their units which concerns virtually all relevant sectors.

The current, traditional measuring system in USA and the country’s slowly progressing metrication is bewildering to European observers. The role of the “U.S. Customary measures” will therefore be considered.

2 IEC’s historic role in the development of the SI base units

The International Electrotechnical Commission (IEC) was founded in 1906 as a forum where scientists, engineers and manufacturers could discuss all aspects of electrotechnical standardization. Its first so-called “commission” on *electric units and standards* met for the first time in London in 1908, where it dealt with units and their physical representation (Teichmann, 2001). The representatives of national institutions or governments adopted one set of fundamental units, defined as decimal multiples of the corresponding electromagnetic “centimetre-gram-second units” (CGS units), and a second set forming a system to represent the fundamental units based on the “international ohm” and the “international ampere”.

Besides this CGS system, further *unit systems in electrodynamics* have been developed (Carron, 2015). They are, however, not relevant in the present *context of IEC work*.

It was not until 1927 that IEC’s TC 1: Advisory Committee on Nomenclature, dealt with the study of various outstanding problems concerning electrical and magnetic quantities and units. Discussions of a theoretical nature were opened at which eminent electrical engineers and physicists considered whether magnetic field strength and magnetic flux density were in fact *quantities of the same nature*. As disagreement continued, the IEC decided to set up a competent task force.

After extensive correspondence among its members, the task force recommended examination of whether it would be appropriate to select, side-by-side with the CGS system, an absolute and rationalized system for practical units. This could be the system proposed by Giovanni Giorgi in 1901 (with the four base units metre, kilogram, second, international ohm) or another system. They would have the advantage of abolishing the set of electromagnetic and electrostatic units found in the CGS system, as well as the need to

introduce at every turn troublesome coefficients (which were all related to the speed of propagation of electromagnetic waves in vacuum).

In 1931, IEC/TC 1 decided to subdivide its field of study into three categories:

- Section A: Vocabulary
- Section B: Electrical and magnetic magnitudes and units
- Section C: Letter symbols.

Only in 1933, Section B submitted in Paris a resolution to replace the CGS system of units by a more practical one: "Section B of the Advisory Committee No. 1 on Nomenclature, having heard with great interest the communication from Mr. Giorgi on the MKS system, and endorsing the resolution adopted by the American section of the International Union of Pure and Applied Physics at Chicago in June 1933, decides to invite the National Committees to give their opinion on the extension of the series of practical units at present employed in electrotechnics by its incorporation in a coherent system having as fundamental units of length, mass and time, the metre, the kilogram and second, and as fourth unit either that of resistance expressed as a precise multiple 10^9 of the CGS electromagnetic unit or the corresponding value of the space permeability of a vacuum".

In 1935 a TC 1 meeting in Scheveningen, Netherlands adopted almost unanimously a system comprising the three units metre, kilogram and second, plus a fourth quantity of electrical nature "to be chosen later". This system was called "Giorgi System". It was also decided to entrust these issues for further processing to an "Advisory Committee on Electric and Magnetic Magnitudes and Units", with the designation IEC/TC 24.

In 1938 at its first meeting in Torquay, England TC 24 recognized that *any one of the practical electrical units already in use* - such as ohm, ampere, volt, henry, farad, coulomb and weber - could equally serve as the fourth fundamental unit. Unfortunately, the Second World War interrupted the work of the IEC, but at its first post-war meeting held in Paris in 1950 the "ampere" was finally chosen. The IEC may claim that its organization was able to provide *the international forum for the relevant discussions to take place*.

3 The International System of Units (SI)

3.1 Giovanni Giorgi's trailblazing contributions

In the middle of the 19th century, the absolute CGS system had been created. The subsequent introduction of the absolute units *into electrodynamics* had many theoretical implications. In particular, J.C. Maxwell developed two systems as extensions into the field of electricity. They were the "absolute electrostatic system" and the "absolute electromagnetic system". At a later stage, O. Heaviside suggested that permittivity and permeability expressed physical properties of the medium, and therefore were *quantities with dimensions* (rather than merely pure numbers).

At the beginning of the 1880s, the Italian scientist and engineer *Giovanni Giorgi* realized the great importance of Heaviside's ideas and confirmed that the *dimensions of a physical quantity* should express its true nature. He succeeded in 1901 in reformulating the existing theory of electromagnetic phenomena as a *four-dimensional theory* (Giorgi, 1901). He introduced – together with the hitherto existing base quantities length, mass and time – a fourth base quantity *of electrical nature*: "It is evident that by assuming the current as a fundamental concept, the definition of any other electromagnetic quantity easily follows".

Giorgi's original paper still seems modern today and deserves to be read with admiration. Its carefully argued presentation reviewed the highly unsatisfactory situation, which then existed with regard to electrical and magnetic units. The proposed unified system of

measuring units was important for science, technology and trade, indeed for every aspect of life where a measure is required. On his proposal Giorgi produced in total no fewer than 40 papers. Many prominent physicists, however, were resolutely opposed to his proposition. The trailblazing contribution relates essentially to four items:

- Unification of the electrostatic and electromagnetic systems
- Elimination of the need for conversion factors
- Elimination of the fractional exponents from dimensional equations
- The conclusion that permittivity and permeability are physical quantities and therefore have dimensions.

In October 1901, Giorgi showed at the congress of the *Associazione Elettrotecnica Italiana (A.E.I.)* in Rome that a *coherent system of units* could be achieved by adding an electric unit to the three mechanical units of the existing CGS system. This event can be considered as the birth of what is now known as the “International System of Units”, or SI. Giorgi anticipated future needs and provided as early as 1901 not only *suggestions* for a coherent system, but indeed a full-fledged solution (Teichmann, 2001). The issue of fundamental units extends well beyond the borderline of electrotechnology into *all technical fields*. Some of these pioneering ideas were fully appreciated only much later and after endless debates: It took in fact *more than thirty years* before they were accepted by the responsible international organizations.

3.2 Today’s SI base quantities and units

The tenth “Conférence générale des poids et mesures” (CGPM; General Conference on Weights and Measures) met in Paris in 1954 and approved the introduction of the *ampere* for “electric current”, the *kelvin* for “thermodynamic temperature”, and the *candela* for “luminous intensity” as additional, dimensionally independent base units (BIPM, 2006a). The organization later on adopted in 1960 a resolution that the system based on the then six base units be given the name “Système international d’unités” (International System of Units), with the international abbreviation “SI”.

It recognized in 1971 the need for a further base unit, and as a result the *mole* (symbol mol) was added as unit for the base quantity “amount of substance”. Today’s *seven base quantities* are tabled in the following (BIPM, 2006b).

<u>Base quantity</u>	<u>Symbol</u>	<u>Base unit</u>	<u>Unit symbol</u>
length	<i>l</i>	metre	m
mass	<i>m</i>	kilogram	kg
time	<i>t</i>	second	s
electric current	<i>I</i>	ampere	A
thermodynamic temperature	<i>T</i>	kelvin	K
amount of substance	<i>n</i>	mole	mol
luminous intensity	<i>I_v</i>	candela	cd

Conventional definitions of the base units: Originally, the base unit *kilogram* had been defined as the mass of a lump of platinum-iridium in a vault in Paris. And a well-known experiment involving the force between two infinite wires defined the *ampere*, the unit of electrical current. The *mole*, on the other hand, was the amount of substance in a system with as many elementary entities as there are atoms in 0,012 kilograms of carbon-12. The *kelvin* related to the temperature and pressure at which water, ice and water-vapor co-exist in equilibrium, known as the triple point of water (Gibney, 2017). By contrast, these units are from now on calculated in relation to constants – for example the ampere is based on the charge of an electron (see Subclause 4.2).

The formal definitions of the SI base units are highly complex and have to be approved by the CGPM. Base units have actually been modified from time to time – but only as *techniques*

of measurement evolved and allowed more accurate realizations (BIPM, 2006b). The CGPM's worldwide network of regional and national metrology organizations is charged with maintaining, developing and disseminating national standards (etalons) and metrological traceability to the SI.

Starting with the fifth edition of BIPM's brochure "Le système international d'unités (SI)" (which was originally published in French only), an additional English version entitled "The International System of Units (SI)" was included. It should be noted that the *French text* must be used when there is doubt about interpretation.

The role of the BIPM includes the establishment of standards for the principal physical quantities, and the maintenance of international prototypes. Its work includes metrological research, making comparisons of international prototypes for verification purposes, and the calibration of standards.

3.3 Common SI derived quantities and units

Non-base quantities are described as *derived quantities*, and they are measured using *derived units*, which are defined as products of powers of the base units (BIPM, 2006a; BIPM, 2014).

Two categories of derived quantities and units are distinguished:

- Derived quantities and units
- Derived units with special names in the SI

Examples of derived quantities and units

<u>Derived quantity</u>	<u>Symbol</u>	<u>Derived unit</u>	<u>Symbol for unit</u>
area	<i>A</i>	square metre	m ²
volume	<i>V</i>	cubic metre	m ³
speed, velocity	<i>v</i>	metre per second	m/s
current density	<i>j</i>	ampere per square metre	A/m ²
luminance	<i>L_v</i>	candela per square metre	cd/m ²
acceleration	<i>a</i>	metre per second squared	m/s ²
magnetic field strength	<i>H</i>	ampere per metre	A/m

Examples of derived units with special names in the SI

These SI derived units have special names and symbols, which are simply a compact form for the expression of *combinations of base units* that are used frequently. Often, the name chosen acknowledges the contribution of a particular scientist. The unit of *force* (the newton), for instance, is named after *Sir Isaac Newton*, one of the greatest contributors in mechanics. The unit of *pressure* (the *pascal*) is named after *Blaise Pascal* for his work in the field of hydrodynamics and hydrostatics. Each of the examples of coherent derived units listed below has its own symbol, but it can also be defined in terms of SI base units.

<u>Derived quantity</u>	<u>Name of derived unit</u>	<u>Symbol for unit</u>	<u>Expression in terms of other units</u>
frequency	hertz	Hz	s ⁻¹
force	newton	N	m kg s ⁻²
pressure, stress	pascal	Pa	N/m ² = m ⁻¹ kg s ⁻²
energy, work	joule	J	N m = m ² kg s ⁻²
power	watt	W	/s = m ² kg s ⁻³
electric potent. difference	volt	V	W/A = m ² kg s ⁻³ A ⁻¹
magnetic flux	weber	Wb	V s = m ² kg s ⁻² A ⁻¹
Celsius temperature	degree Celsius	°C	K

It should be noted that a number of *non-SI units* still appear frequently in the scientific, technical and commercial literature. Some of them, in particular the units of time, are so

widely used in everyday life and embedded in history and culture, that they will continue to be used in the foreseeable future. A number of accepted non-SI units are listed in Appendix A: Non-SI units accepted for use with the IS. However, with a few exceptions, SI units are always to be preferred.

4 Recent revision of the SI

4.1 Background

On 16 November 2018, in a landmark decision, the CGPM voted unanimously in favor of revised definitions, which the *International Committee for Weights and Measures (CIPM)* had proposed earlier that year. The CGPM thereby changed the world's definition of *the kilogram, the ampere, the kelvin and the mole* (BIPM, 2018b). The revised system does not depend any longer on *physical objects*. Instead, it is based entirely on *the speed of light or other "constants" of physical science*, resulting in a measurement system that might truly and finally be "for all times, for all peoples".

4.2 New, respectively unchanged definitions of the SI base units

The four SI base units *kilogram, ampere, kelvin and mole* were redefined. Their new definitions are based on fixed numerical values of four constants: the Planck constant (h), the elementary charge (e), the Boltzmann constant (k), and the Avogadro constant (N_A), see Appendix C: Constants providing the basis of the four revised SI base units.

These definitions came into force on 20 May 2019. Accordingly, the definitions of *all seven base units of the SI* are now uniformly expressed using the explicit-constant formulation (Gibney, 2017). It should be noted that, for measurements on conventional scales, the existing definitions of the SI units suffice. But they are poor tools for modern science at the extremes. According to metrologists, basing units on specific points or materials can be troublesome. The unchanged/changed definitions are the following:

Metre (m)

Measures: Length

Requires: Speed of light

Unchanged definition: Length of the path travelled by light in a vacuum in $1/299\,792\,458$ seconds

Kilogram (kg)

Measures: Mass

Requires: Planck's constant (h)

New definition: One kilogram is Planck's constant divided by $6.626\,070\,15 \times 10^{-34} \text{ m}^2 \text{ s}$

Second (s)

Measures: Time

Requires: Hyperfine transition frequency of the caesium-133 atom

Unchanged definition: Duration of $9192\,631\,770$ cycles of the radiation corresponding to the transition between two hyperfine levels of caesium-133

Ampere (A)

Measures: Current

Requires: Charge on the electron (e)

New definition: Electric current corresponding to the flow of $1/(1.602\,176\,634 \times 10^{-19})$ elementary charges per second

Kelvin (K)

Measures: Temperature

Requires: Boltzmann's constant (k)

New definition: Equal to the change in thermal energy of $1.380\,694 \times 10^{-23}$ joules

Mole (mol)

Measures: Amount of substance

Requires: Avogadro's constant (N_A)

New definition: Amount of substance of a system that contains $6.022\,140\,76 \times 10^{23}$ specified elementary entities

Candela (cd)

Measures: Luminous intensity

Requires: Luminous efficacy of monochromatic light of frequency 540×10^{12} Hz

Unchanged definition: Luminous intensity of a light source with a frequency 540×10^{12} Hz and a radiant intensity of $1/683$ watts per steradian

The constants, which provide the basis of the *four revised* SI base units are listed in Appendix C.

5 Responsible committees in the World Standards Corporation

5.1 Methodology for standardizing physical quantities and their units

Standardization in the field of physical quantities and their units requires comprehensive coordination. The *World Standards Cooperation* (WSC) provides the necessary high-level collaboration between the IEC, ISO and ITU. Under this banner, the three organizations preserve their common interests in strengthening and advancing the voluntary consensus-based International Standards system (IEC, ISO and ITU, 2018). Their initiatives include workshops, education and training, as well as the promotion of the *International Standards System*.

By far most TCs develop “product standards” in *their respective areas of expertise*. For consistency, the use of quantities and units by these product-oriented or “vertical” committees has to be reviewed. Conversely, it is obvious that that *new work* in the field of quantities and units should always reflect trends, which are engendered by vertical committees.

As committees with “horizontal” responsibilities (i.e. covering matters of wide-ranging nature and applicable by many product-oriented committees), IEC/TC 25, ISO/TC 12 and ITU Study Group 17 are in charge of *all questions concerning the SI*. Their key objective is at present *to harmonize* the global standards of all technical sectors on the basic subject “Quantities and units”.

- For standards related to fundamental concepts, a *broad and truly international consensus* has to be reached because otherwise the member countries of the originating organizations, respectively the other international organizations concerned would not be willing to adopt them. A special methodology with the following features is therefore applied in the project management of these committees:
- Requests for new quantities and units, and related letter symbols may be submitted by *any TS/SC or National Committee (NC)*.
- Committee Drafts are prepared either by the project leader or a Working Group, in which experts from the TCs/SCs, respectively from the other organizations concerned may participate (IEC, 2018b).
- NCs consult their experts in the field of ISO/TC 12, IEC/TC 25, ITU-T and *any other committees concerned* in parallel and submit their collated comments in a *single*

document. The resulting draft is then circulated to all parties concerned, including liaison organizations.

Note:

It has been observed that many experts in horizontal committees (in particular ISO/TC 12 or IEC/TC 25) are, inevitably, specialists *only in* their limited *fields* of science and technology, and that they may hence be inclined to sub-optimize the system of “Quantities and units” to fit their own field of interest. ISO is probably more concerned in this respect than IEC, because it is responsible for far more technical sectors than IEC.

5.2 Committee IEC/TC 25: Quantities and units

IEC/TC 25 was established in 1925. Its original title, “Quantities and units, and their letter symbols” was revised in 2008 to its present wording “Quantities and units”. Its scope (which is actually under revision) reads: “To prepare international standards on quantities and units to be used in electrical technology. Such standards may relate to their definitions, names, letter symbols and use; to the relations in which they appear; and to the signs and symbols used with them”.

The committee had, as of this writing, 15 P-members (Participating members who have the obligation to vote at all stages and to contribute to meetings) and 14 O-members (Observer members who follow the work as an observer and having the right to submit comments and to attend meetings), see (IEC, 2018a; b).

USA is P-member; Liberia and Myanmar are non-members (see Subclause 7.1). Close cooperation of IEC/TC 25 is required with IEC/TC 1: Terminology, and ISO/TC 12; external technical liaison is maintained with organizations such as

- BIPM Bureau international des poids et mesures - International Bureau for Weights and Measures
- ITU International Telecommunication Union
- IUPAP International Union of Pure and Applied Physics
- OIML Organisation Internationale de Métrologie Légale – International Organization of Legal Metrology

Major current concerns are the following: The expansion of applications of electromagnetic and optical technologies to communication and information technology (especially data transmission, processing and storage) requires the timely development of standards for the associated quantities and units. The needs of such technologies, particularly in telecommunications, telebiometrics related to human physiology, and information technology have the highest priority. Power technology is also important. Teachers and students, especially in electrical engineering and physics constitute a major target group. The performance of IEC/TC 25, however, is sometimes hampered by lacking support by NCs.

5.3 Committee ISO/TC 12: Quantities and units

The scope of ISO/TC 12 reads: “Standardization of units and symbols for quantities and units (and mathematical symbols) used within the different fields of science and technology, giving, where necessary, definitions of these quantities and units. Standard conversion factors between the various units” (ISO, 2018).

As of this writing, some 20 countries were P-members, and some 30 were O-members. It should be noted that USA is P-member; Liberia and Myanmar are non-members. The P-members represent more than 50 per cent of the world’s population, the O-members about another 25 per cent. The committee has technical liaisons with nine other ISO/TCs, with ISO/IEC JTC 1: Information technology, and necessarily with IEC/TC 25. Further important liaisons concern BIPM, ITU and OIML.

Recent trends in the need for standardization of quantities and units as expressed by stakeholders may stimulate new work items for ISO/TC 12. In particular, modern data collection increasingly integrates data from multiple systems, both in laboratory set-ups and internet search engines. Without standardization, there can be a lack of consistency – both in terms of metadata and document formats. Furthermore, the committee is at present working closely with the health informatics community (ISO, 2017).

5.4 ITU-T Study Group 17: Security

Work to build confidence and security in the use of information and communication technologies continues to intensify in a bid to facilitate more secure network infrastructure, services and applications. So far, over 170 standards focusing on security have been published (ITU, 2018).

ITU-T SG 17 coordinates security-related work *across all ITU-T Study Groups*. Often working in cooperation with other standards development organizations and various information and communication technology industry consortia, SG 17 deals with a broad range of standardization issues. To give a few examples, it is currently working on cybersecurity; security management; security architectures and frameworks; countering spam; identity management; the protection of personally identifiable information; and telebiometrics. The latter item also includes the quantities and units concerned with effects on a human being caused by the use of a telebiometric device.

6 Harmonized global Joint Standards Series ISO/IEC 80.000: Quantities and Units

The harmonization of two fundamental standards was approved by the Technical Management Boards of both ISO and IEC, namely ISO 31: Quantities and units, respectively IEC 60027: Letter symbols to be used in electrical technology. The joint publication with the reference “ISO/IEC 80.000: Quantities and Units” consists at present of 13 parts. In the table below, the information in parentheses indicates the *origin* of their technical content.

- Part 1: General, 2009 (IEC 60027-1 and 3, ISO 31-10)
- Part 2: Mathematical signs and symbols to be used in natural sciences and technology, 2009 (IEC 60027-1, ISO 31-1)
- Part 3: Space and time, 2006 (ISO 31-1 and 2)
- Part 4: Mechanics, 2006 (ISO 31-3)
- Part 5: Thermodynamics, 2007 (ISO 31-4)
- Part 6: Electromagnetism, 2008 (IEC 60027-1, ISO 31-5)
- Part 7: Light and radiation, 2008 (ISO 31-6)
- Part 8: Acoustics, 2007 (ISO 31-7)
- Part 9: Physical chemistry and molecular physics, 2009 (ISO 31-8)
- Part 10: Atomic and nuclear physics, 2009 (ISO 31-9 and 10)
- Part 11: Characteristic numbers, 2008 (ISO 31-12)
- Part 12: Condensed matter physics, 2009 (ISO 31-13)
- Part 13: Information science and technology, 2008 (IEC 60027-2 and 3)
- Part 14: Telebiometrics related to human physiology, 2008 (IEC, withdrawn)

The prefix before the number 80.000 of a given part is *either ISO or IEC*, but not the double ISO/IEC prefix. Most countries of the world have now adopted ISO/IEC 80.000 as their *national standards or as national law*. They give terms, definitions, recommended symbols, units and any other important information related to quantities used in science, engineering, metrology and industry. They are a reference for those writing scientific or technical documents, textbooks, standards and guides (IEC, 2017).

Note:

In ITU, an adapted version of Publication IEC 80.000-14 is still in force.

7 Use of non-metric unit systems

7.1 Countries using a non-metric system of units

By far most of the world is on the metric system. It would, however, be an oversimplification to say that *Liberia, Myanmar and the US* are “the only three countries not using the metric system”. Rather, the actual situation is the following:

- Liberia uses the “U.S. Customary system” (see Appendix B), and for certain purposes metric units.
- Myanmar uses the UK Imperial System, and similarly for certain purposes metric units.
- In USA (plus some Caribbean islands under American influence) the “U.S. Customary system” is used. But the metric system is already used for many purposes, just *not officially*. - It should be noted in this context that the US has actively participated in the recent revision of the SI (see Clause 4).
- In many other countries, that *do officially use metric units*, traditional units are still used for many purposes, though sometimes illegally. For information on units outside the SI see Appendices A and B.

There are three well-known examples where non-SI units are normally used everywhere, certainly by tradition (BIPM, 2006a):

- In navigation, the units “nautical mile” and “knot” are used for distance and speed, respectively.
- Altitudes are given in the unit “foot”, which has neither a simple relation to the nautical mile nor the meter.
- Human blood pressure in medicine is measured in the unit “millimeter of mercury”, with the symbol “mm Hg” (respectively, in USA in “inches of mercury”, with the symbol “in Hg”).

7.2 America’s adherence to its traditional measurement system

The U.S. customary units are the system of measurement commonly used in USA. It developed from the English units, which were in use in the British Empire before the U.S. became an independent country. However, the UK system of measures was overhauled in 1824 to create the “imperial system”, changing the definitions of some units. Therefore, while many U.S. units are essentially similar to their imperial counterparts, there are still significant differences between the systems.

From a European point of view, the U.S. Customary system of measurement is a unique and odd thing to behold with its esoteric, inconsistent elements: There are twelve inches in a foot, three feet in a yard, sixteen ounces in a pound, but one hundred pennies to the dollar (see Appendix B: Conversion from U.S. Customary measures to metric). For something as elemental as counting and estimating the world around, it seems – at least to Europeans - like a confusing tool to use. Although the use of the metric system has been sanctioned in the USA by law since 1866 already, the country has been slow in displacing its U.S. Customary system. For a time in the 1970s, America appeared to be ready to make the switch, yet it never happened. The reasons for the current status may go to the root of who the Americans think they are, just as the measurements are woven into the way people think (Marciano, 2014).

To certain contemporary Americans, perhaps, “superfluous uniformity” appears to be an enemy of a better life. In this perspective, advocating a “metric America” could almost mean to be in favour of a *global monoculture*. It is true that during a long period of time the metric

system had succeeded solely in countries headed by a king, Kaiser, or emperor, and even then only *by force of law*. The US Metric Association (USMA) is firmly convinced that metrication *will be inevitable* (USMA, 2018; 2019).

Note:

George Orwell's "Nineteen Eighty-Four" imagined that the metric system had been imposed on America and Britain by the totalitarian regime of "Big Brother". The system's nomenclature fit in perfectly with the structure of "Newspeak", Orwell's satire to invent a rational version of English to serve as an international auxiliary language. The association of the meter with authoritarianism by Orwell was in fact not entirely unfair, as it could still be said when the novel was published in 1949 that only few democracies had adopted the meter.

In 1974, while senators and congressmen considered the issue of measurement systems without major results, America was going – at least in part – metric on its own: Certain car manufacturers, pharmaceutical manufacturers and other industries began – for economic reasons – switching their operations to metric. Generally speaking, there is a slowly increasing acceptance of the metric measuring system in science, medicine and government.

7.3 Arguments and objectives of the US Metric Association

The USMA points out that many Americans are not aware of the extent of the actual degree of metric usage in the country. The association's arguments are essentially the following:

- Metric is already required along with inch-pound units on most consumer products (for instance beverages, foods, health and beauty care, as well as cleaning products).
- About 50 per cent of measures in the US are now metric. Many of those measures are already used in the fields of science, engineering, manufacturing and international trade.
- All inch-pound measures are defined and calibrated to the *SI metric system*.
- The metric measuring system is used predominantly in *the rest of the world*, with the US being the only major holdout.
- The Metric Conversion Act, first passed in 1975 and amended in 1988, *is still in effect in the US*. Accordingly, the metric system is *in principle* the preferred system of measurement in the US, and encouraged by the government.

Maintaining dual systems in manufacturing, science and government rarely makes sense. But the fact that it is good to go metric in such areas is not necessarily an argument for using it *everywhere* in the population's daily life (Marciano, 2014). In order to accomplish the "completion of the ongoing US conversion to the metric system", USMA's main purpose and objectives are as follows:

- To furnish a national medium for uniting the efforts of individuals, societies, educational and research institutions, professional associations and government agencies interested in promoting the use of the metric system of measurement
- To determine the best ways and means for the adoption of the metric system in the United States
- To prepare, publish and otherwise disseminate such information to the general public as will set forth the advantages of early adoption and use of the metric system
- To prepare and publish training aids for teaching the metric system in schools and to the general public
- To broaden and sustain interest in the use of the metric system by means of meetings, lectures, discussions and audio-visual education and to publish bulletins, pamphlets, newsletters and correspondence
- To offer citations and awards to individuals and organizations for their outstanding contributions in the promotion of the use of the metric system.

The question could now be asked whether or not the redefinition of the SI base units kilogram, ampere, kelvin and mole will have an impact on the use of the U.S. Customary system. The

answer is “no” because these base units are the basis also for the U.S. Customary system, and because they have *not changed in value*.

8 Conclusions

8.1 Standardizing physical quantities and their units

The history of the metric system presents almost a human drama, replete with great inventors, visionary kings and presidents, obsessive activists, and science-loving technocrats. Giovanni Giorgi’s case shows that being ahead of one’s time can draw far more criticism than being behind. But fortunately, he finally had the satisfaction of witnessing how, after many years of seemingly endless debate his original proposals were accepted without major changes.

The standardization of units and their symbols for any physical quantity (that is, any property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference) has general impact ranging from fundamental science all the way up to society.

It would be impossible to develop the standards family ISO/IEC 80.000 on a *commercial basis*. The necessary expertise in the numerous specialized subject fields has to be contributed by highly qualified experts in *each relevant sector and from around the world*. Their balanced participation requires a specially developed methodology. This is the only way to avoid that the ISO/TC 12, IEC/TC 25 or ITU-T SG 17 experts have to trespass beyond the limits of their competence.

8.2 Significance of the International System of Units (SI)

SI base units and the different types of SI derived units have the important advantage of forming a *coherent set*, with the effect that unit conversions are *not required* when inserting particular values for quantities in quantity equations. SI units are therefore recommended for use throughout science, technology and commerce. They are approved internationally by the CGPM, and actually provide the reference in term of which all other units – *including those of the non-metric U.S. Customary system* – are defined.

Stakeholders of the standards on physical quantities and their units are – directly or indirectly – practically all industries of the world, governments and consumers. In our time trade would be hardly possible without the tool of standardized, widely accepted quantities and units. As time goes by, new products will appear on the market. They will successively be adapted to metric size widely over the globe. By legislation, individual countries have established rules concerning the use of units on a *national basis*, either for general use or for specific areas such as commerce, health, safety or education.

The overall importance of the SI reveals itself by the fact that it is *prescribed* in the ISO/IEC Directives: *All International Standards* shall use quantities and units as given in the Joint Standards Series ISO/IEC 80.000. This unit system is indeed not only of *economic nature*, but it also facilitates improvements of communication with respect to *cultural, scientific and political matters*.

The unification of measurements on a global scale, for all domains of activities, is vital to industries. It should be noted that there are in all only four systems of writing that bridge *all linguistic barriers* regardless of the alphabet used in the languages concerned:

- The set of mathematical signs and symbols
- The SI
- The symbols for chemical elements
- The way of writing notes for music

The importance of the *standards series ISO/IEC 80.000* is demonstrated by the fact that it covers the first three systems: Only music is out of its scope.

The undisputed usefulness of the *metric system*, however, does not change the fact that it is highly artificial. And its universality should not lead to the notion that decimal systems are *the only way* of perceiving the world.

8.3 Redefinition of four SI base units: kilogram, ampere, kelvin and mole

In November 2018, a group of 60 BIPM member countries made history. With a unanimous vote on the redefinition of the world's measurement system, they finally realized scientists' 150-year dream of a system based entirely on *unchanging, fundamental properties of nature*. In fact, the SI changed in a way that is more profound than anything else since its establishment following the French Revolution (NIST, 2018b). The new definitions of kilogram, ampere, kelvin and mole aim to improve the SI without changing the *size* of any units, thus ensuring full continuity with existing measurements. The decision of the 26th BIPM meeting means that *all SI units* will now be defined in terms of *constants that describe the natural world*. This fact will assure the future stability of the SI and open the opportunity for the use of new technologies, including quantum technologies, to *implement* the definitions.

This redefinition will certainly not affect everyday measurements, and furthermore *no immediate effect* will be noticed by consumers. But it will enable scientists working at the highest level of precision to do so in multiple ways, *at any place or time and on any scale*, without losing accuracy. The biggest expected change will likely be for manufacturers of scientific instruments, who may need to adapt their products in coming years to accommodate the revised SI method for better determining measures of electric quantities such as the ampere, the volt and the ohm.

8.4 Current situation in USA

The USA is an active P-member in ISO/TC 12, IEC/TC 25 and ITU-T SG17. A slowly, but steadily increasing acceptance of the metric system in science, medicine, government and certain sectors of the American industry can be observed. The American Metric Association strongly recommends *comprehensive metrication*. But it will undoubtedly be a while before road signs and weather reports will be drawn up in metric.

America's advocates of metrication claimed that the adoption of the metric system was *inevitable*, and that *not adopting it rapidly* would lead to economic ruin. It seems that the country has never gone mainly metric simply because *it never had to*. The uncompromising advocates were certainly misguided in thinking that metrication had to be an *all-or-nothing proposition*. It is true that the USA has, at present already, gone metric where metrication has obviously been useful (the best-known example may be space travel). And Liberia and Myanmar are further examples of countries using two systems. The question could now be asked if the progress of America's metrication will in future be affected by the growing impact of information technology.

According to USMA, going metric pays off (USMA, 2019). Longer-term benefits of using a single measurement system prevail under short-term costs of metrication especially in large US companies.

8.5 Cultural aspects of international standardization

Generally speaking, active participation in global standardization is in the best interest of any country. And although the field of Physical Quantities and Units is *remote from immediate financial rewards*, it does deserve the wholehearted support by all stakeholders involved. Finally, the long history of the metric system confirms in an impressive manner that the *ability*

to find a consensus despite major controversies is definitely a core virtue of international standardization, in a way a “cultural technique”.

The present study also suggests that contributing to global horizontal technical/scientific standardization is rewarding and inspiring.

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Appendix A: Non-SI units accepted for use with the SI

The CGPM has stated that, for a variety of reasons, a number of *non-SI units* are accepted for use with the SI. Many of them are still in use, others are required for the interpretation of scientific texts of historical importance, and some are used in specialized areas such as medicine. Yet the use of the equivalent SI units is preferred for modern scientific texts (BIPM, 2006a; 2014). In this context, three categories of non-SI units are distinguished:

- Non-SI units accepted for use with the SI
- Non-SI units accepted for use with the SI, whose values in SI units must be determined experimentally
- Certain other non-SI units accepted for use with the SI

Examples of non-SI units accepted for use with the SI

Quantity	Name of unit	Symbol for unit	Value in SI units
time	minute	min	1 min = 60 s
	hour	h	1 h = 60 min = 3600 s
	day	d	1 d = 24 h = 86 400 s
area	hectare	ha	1 ha = 1 hm ² = 10 ⁴ m ²
volume	litre	L	1 L = 1 dm ³ = 10 ³ cm ³ = 10 ⁻³ m ³
mass	tonne	t	1 t = 10 ³ kg

Example of non-SI units accepted for use with the SI, whose values in SI units must be determined experimentally

Quantity	Name of unit	Symbol for unit	Value in SI units
energy	electronvolt	eV	1 eV = 1,602 176 53 (14) x 10 ⁻¹⁹ J

Examples of other non-SI units accepted for use with the SI

Quantity	Name of unit	Symbol for unit	Value in SI units
pressure	bar	bar	1 bar = 10 ⁵ Pa
distance	nautical mile	M	1 M = 1852 m
speed	knot	kn	1 kn = (1852/3600) m/s

Appendix B: Conversion from U.S. Customary measures to metric

The table below shows a selection of commonly used units of the U.S. Customary system, together with their symbols and the equivalent in SI units (NIST, 2018a; Wikipedia, 2018).

<u>Quantity</u>	<u>Unit (Symbol)</u>	<u>Equivalent in SI units</u>
length	foot (ft) = 12 in	0,3048 m
	yard (yd) = 3 ft = 36 in	0,914 m
	inch (in) = 1/12 ft	2,54 cm
	mile (mi) = 1.760 yd = 5.280 ft = 63.360 in	1,609 km
	mil = 1/1000 in	
area	square foot (ft ²)	0,0929 m ²
	square yard (yd ²)	0,8361 m ²
	square inch (in ²)	6,452 cm ²
	acre (ac) = 43.560 (ft ²)	4046,7 m ²
volume	gallon (gal)	3,785 L
	pint, liquid (pt)	0,473 L
	cubic foot (ft ³)	28,32 L
temperature	degree Fahrenheit	$5/9 (°F - 32) + 273,15 K$
weight	pound (lb)	0,4536 kg
	ounce (oz) = 1/16 lb	0,02835 kg
	short ton = 2000 lb	907,18 kg
force	pound-force (lbf)	4,448 N
pressure	pounds per square inch (psi)	6,895 Pa
	inches of mercury (in Hg) = 0,491 psi	25,4 mm Hg
	atmosphere (atm)	1,013 bar
energy	foot-pound (ft-lb)	1,356 J
	British thermal unit (Btu)	1055 J = 0,252 kcal
power	horsepower (hp)	0,7457 kW

Appendix C: Constants providing the basis of the revised SI base units kg, A, K and mol

These constants are central to a set of well-established scientific principles in physical science, and the resulting global measurement system may indeed be expected to be final (Gibney, 2017).

Planck's constant

The Planck constant (symbol h) is a fundamental physical constant characteristic of the mathematical formulations of quantum mechanics, which describes the behavior of particles and waves on the atomic scale. The new definition of the unit *kilogram* (kg) is based on this constant:

$$h = 6.626\ 070\ 15 \times 10^{-34} \text{ J Hz}^{-1}$$

Elementary charge

The elementary charge (symbol e) is an apparently fundamental constant that is the smallest known quantity of electricity. It is either positive or negative (as the positron or electron). The new definition of the unit *ampere* (A) is based on the elementary charge:

$$e = 1.602\ 176\ 634 \times 10^{-19} \text{ C}$$

Boltzmann's constant

The Boltzmann constant (symbol k) is a fundamental constant of physics occurring in nearly every statistical formulation of both classical and quantum physics. The new definition of the unit *kelvin* (K) is based on this constant:

$$k = 1.380\ 649 \times 10^{-23} \text{ J K}^{-1}$$

Avogadro's constant

The Avogadro constant (symbol N_A) is the number of units in one mole of any substance (defined as its molecular weight in grams). The units may be electrons, atoms, ions or molecules. The new definition of the unit *mole* (mol) is based on this constant:

$$N_A = 6.022\ 140\ 76 \times 10^{23} \text{ mol}^{-1}$$

Acronyms

BIPM	Bureau international des poids et mesures - International Bureau for Weights and Measures
CGPM	Conférence générale des poids et mesures - General Conference on Weights and Measures
CGS system	centimetre – gram – second system
CIPM	Comité international des poids et mesures - International Committee for Weights and Measures
ITU	International Telecommunication Union
ITU-T	International Telecommunication Union - Standardization Sector
IUPAP	International Union of Pure and Applied Physics
NC	National Committee
OIML	Organisation Internationale de Métrologie Légale - International Organization of Legal Metrology
O-member	Observer member
P-member	Participating member
SC	Subcommittee
SI	Système international d'unités - International System of Units
TC	Technical Committee
USMA	US Metric Association
WSC	World Standards Cooperation