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Review Article

Metrology in the light of new definitions of SI units

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ABSTRACT

The science of measurement, which we call metrology, is used to guarantee the accuracy and consistency of measurement systems, in other words, to ensure traceability. Quantum physics, the science of atoms and fundamental particles discovered in the first half of the 20th century, enables surprising developments in the world of metrology. In this article, the importance of metrology is emphasized and the developments are presented in order to pave the way for newly developing technologies in science (such as quantum) and to ensure that they take the right path. The revision of SI units in the field of metrology in the light of developing science was detailed and compared. It was examined why the redefined SI units were defined with universal constants rather than physical objects. The studies of national metrology institutes, centers and laboratories, which lead metrology studies and are in charge in each country, were compiled. The effects of metrology were examined, especially in sensors and optical systems that incorporate rapidly developing quantum-based technologies.

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1. Introduction

The science of measurement, which we call metrology, is used to guarantee the accuracy, standardization and consistency of measurement systems, in other words, to ensure traceability. Metrology science covers all activities of measurement, verification and calibration. Establishment of measurement and calibration systems are conducted by national metrology institutes in each country. It is the duty of metrology to use scientifically accepted measurement and calibration methods to protect legal rights. High accuracy in scientific measurements, in other words low uncertainty, and the accuracy of traffic radars, scales, car tire pressure meters, devices used in hospitals (x-ray, MRI,

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ultrasound, etc.), electricity, gas and water meters are ensured by the science of metrology. Guaranteeing measurement results in military, industrial and healthcare fields is possible with the use of metrology only. The fact that every measurement has uncertainty is an important finding in terms of metrology. In other words, a measurement result without a declared uncertainty value is scientifically meaningless.

Modern metrology began with the motivation to standardize the unit of length and continued with the establishment of the metric system in 1795. After many countries adopted the metric system until 1875, the Meter Convention was signed and the Bureau International des Poids et Mesures (BIPM) was established to ensure compatibility between countries (SI Brochure, 2022). In 1960, as a result of the decision taken at the 11th General Conference on Weights and Measures (CGPM), the International System of Units (SI) was established (Barrell, 1961).

The SI consists of a coherent system of units of measurement covering seven base units. These units are time, length, mass, electric current, thermodynamic temperature, amount of matter and light intensity, and their units are second (s), meter (m), kilogram (kg), ampere (A), kelvin (K), mole (mole), and candela (cd) respectively as tabulated in Table 1. A required number of consistent derived units can be created from these seven base units. For example, more than twenty coherent derived units have been given special names and symbols like force, F ($kg.m/s^2$) and charge (A•s). Standard units have been created to allow consistency and communication of measurement results. Units must be presented according to BIPM SI brochure and International Vocabulary of Metrology (VIM) (Clifford, 1985; BIPM document, 2021).

Table 1. Seven base SI units

Quantity	Name	Symbol
time	second	s
length	meter	m
mass	kilogram	kg
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

Recently, physical objects (artefacts) were referenced in the definitions of the basic units in SI. For example, until 1983, the meter was defined as the length of a platinum-iridium rod that was stored under special environmental conditions to prevent wear and tear over time. However, with the development of science, basic units began to be redefined in terms of natural constants to make them more stable. Similarly, the unit of mass, kg, was defined by a cylindrical platinum-iridium block that had been stored in Paris since 1879 and had nearly 40 copies in scientific institutions around the world. In comparisons made at regular intervals, it was seen that their weights differed on the order of micrograms compared to each other. Another example, the unit of thermodynamic temperature. It is defined as “one 273.16th of the thermodynamic temperature of the triple point of water (273.16 °K), where it exists simultaneously in solid, liquid and gas phases” (Peruzzi, 2018; Peruzzi et al., 2018; Preston-Thomas, 1990).

A consequence is that as science and technologies develop and new and superior realizations will be needed. Higher accuracies are a must in measurement systems. For this reason, metrology is trying new formations and approaches which for the redefinition of SI units as example.

2. Methodology

2.1. Comparison of Old and New Definitions of SI

The redefinition of SI units, which were used as reference for physical objects in the past, began to take its current form in 1967, when the second was redefined in terms of the frequency of light emitted from the cesium (Cs) atom, and in 1983, the meter was redefined in terms of the speed of light. On November 16, 2018, representatives from sixty countries met at the CGPM in France and decided to make changes to the International System of Units (SI). Kilogram, ampere, mole and kelvin were redefined as seen in Figure 1 and Table 2. The seven revised SI units are defined using unchanging quantities, or universal constants, such as the speed of light, Planck's constant, and the amount of electric charge on an electron.

The decisions taken at the 26th meeting of the CGPM is briefly as the following:

- The kilogram will be redefined in terms of Planck's constant (h),
- The ampere will be redefined in terms of the fundamental electric charge (e), (Brun-Picard et al., 2016)
- Kelvin will be redefined in terms of Boltzmann constant (k) (Fischer, 2016; Machin, 2018)
- The mole will be redefined in terms of Avogadro's constant (N_A).

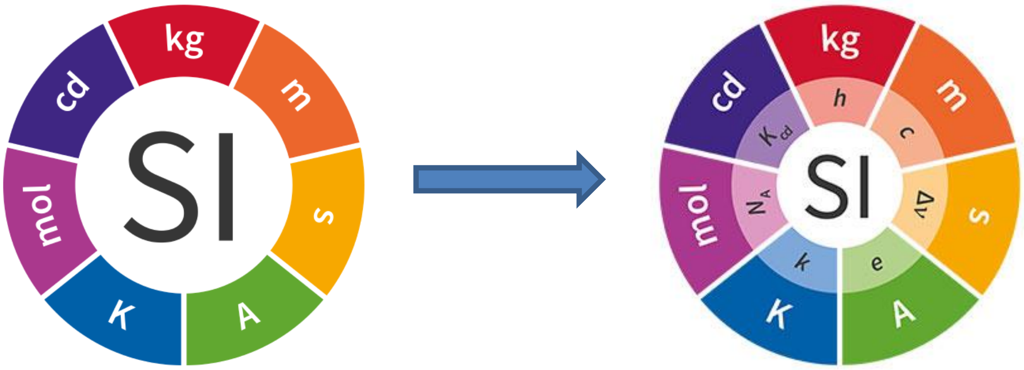

Figure 1. Redefinition of SI units

Table 2. Redefinition of SI units based on universal constants

Defining constant	Symbol	Exact value
Hyperfine transition frequency of Cs	$\Delta\nu_{\mathrm{Cs}}$	9192631770 Hz
Speed of light	c	299792458 m/s
Planck constant	h	6.62607015×10^{-34} J·s
Elementary charge	e	$1.602176634\times10^{-19}$ C
Boltzmann constant	k	1.380649×10^{-23} J/K
Avogadro constant	N_A	6.02214076×10^{23} mol^{-1}
Luminous efficacy of 540 THz radiation	K_{cd}	683 lm/W

As of May 20, 2019, in addition to the 4 newly redefined basic units (kilogram, ampere, kelvin and mole), the other 3 units were also reworded to emphasize their dependence on unchanging quantities and universal constants as tabulated in Table 3. The most radical change occurred in defining the Kilogram Prototype in terms of Planck's constant rather than its mass. Another important change is in temperature which is a measure of the thermal energy per particle in a substance. The average kinetic energy K of the particles is directly proportional to the temperature T in Kelvin, with the proportionality constant being the Boltzmann constant k. This definition emphasizes the relationship between temperature and the microscopic behavior of particles, providing a more fundamental understanding of temperature in terms of the energy of individual particles within a substance.

Table 3. The old and new definitions of SI units

SI Unit	Old definition	Redefinition/New definition
Second (definition is identical but reworded)	Second is the duration of 9,192,631,770 periods of radiation corresponding to the transition between two extremely thin levels of the ground state of the Cs-133 atom	The constant numerical value of the Cs frequency $\Delta\nu Cs$ (the frequency of the ground-level hyperfine transition of the Cs-133 atom), expressed in Hz (1/s), is defined as 9,192,631,770.
Meter (definition is identical but reworded)	Meter is the distance traveled by light in vacuum in the time interval of 1/299,792,458 of 1 second.	The constant numerical value of the speed of light in vacuum, expressed in units of ms^{-1}, is defined as 299,792,458.
Mass (the basic unit of mass becomes dependent on the basic units of time and length)	Kilogram is a unit of mass. It is equal to the mass of the international kilogram prototype.	The constant numerical value of Planck's constant h, expressed in units of Js (kgm^2s^{-1}), is defined as $6.62607015x10^{-34}$.
Ampere (since the old definition referred to force, it was dependent on the basic units of mass, time, and length. In the new definition, only reference is made to the second.)	Ampere is the constant current that causes a force of $2x10^{-7}$ N to act on each meter of the conductive wires when two infinitely long conductive wires with negligibly small cross-sectional areas are positioned parallel in space, one meter apart.	The constant numerical value of the fundamental electric charge e, expressed in units C (As), is defined as $1.602176634x10^{-19}$.
Kelvin (new definition refers to the basic units of mass, length and time)	Kelvin is one 273.16th of the thermodynamic temperature of the triple point of water (the pressure and temperature value at which solid, liquid and gaseous states can coexist).	The constant numerical value of the Boltzmann constant, expressed in units JK^{-1} ($kgm^2s^{-2}K^{-1}$), is defined as $1.380649x10^{-23}$.
Mole (there is no reference to any other SI unit, the mass of the carbon-12 atom is defined as exactly 12 daltons (Da).	A mole is the amount of substance in a system containing as many elementary particles as there are atoms in 12 grams of carbon-12. When using moles, basic particles must be specified. These elementary particles can be atoms, molecules, ions, electrons, other particles, or specific groups of these particles.	One mole contains exactly $6.02214076x10^{23}$ elementary particles. This number is the constant numerical value of Avagadro's constant NA when expressed in mol-1 units and is called Avagadro's number.
Candela (definition is identical but reworded)	Candela is the luminescence intensity of a source emitting monochromatic radiation with a frequency of $540x10^{12}$ Hz in a certain direction and whose radiant intensity in this direction is 1/683 watt/steradian.	In a specific direction, Candela is defined by taking the constant numerical value of the luminescence efficiency (Kcd) of monochromatic radiation with a frequency of $540x10^{12}$ Hz in lmW^{-1} ($cdsrkg^{-1}m^{-2}s^3$) unit as 683.

With the introduction of new SI definitions, metrology institutes went to new formations. Laboratories that were formerly established on a unit realization basis began to transform into quantum metrology laboratories or departments.

In 2009, the German Metrology institute PTB established a joint Institute for Experimental Quantum Metrology (QUEST) with Leibniz Universität Hannover (PTB, 2024). It was targeted to establish atomic quantum systems for metrology and to use many-body systems and quantum correlations for fundamental physics tests and precise measurements. Also ensuring and developing electrical quantum standards at the highest level, which is the basis for the implementation of electrical units in the SI system is aimed.

Three working groups were established on:

- Quantum Hall Effect (Resistance and Current)
- Josephson Effect (Voltage)
- Quantum Impedance

British metrology institute NPL has established the Advanced Quantum Metrology Laboratory (AQML) for the testing and evaluation of watches, watch sub-components and solid-state quantum technologies (NPL, 2024a; NPL, 2024b). UK universities will thus be able to accurately set the time standard required for physical or sensitive spectroscopy and improve their research capabilities as seen in Figure 2. For this purpose, NPL has established many departments and sub-sections as seen in Table 3.

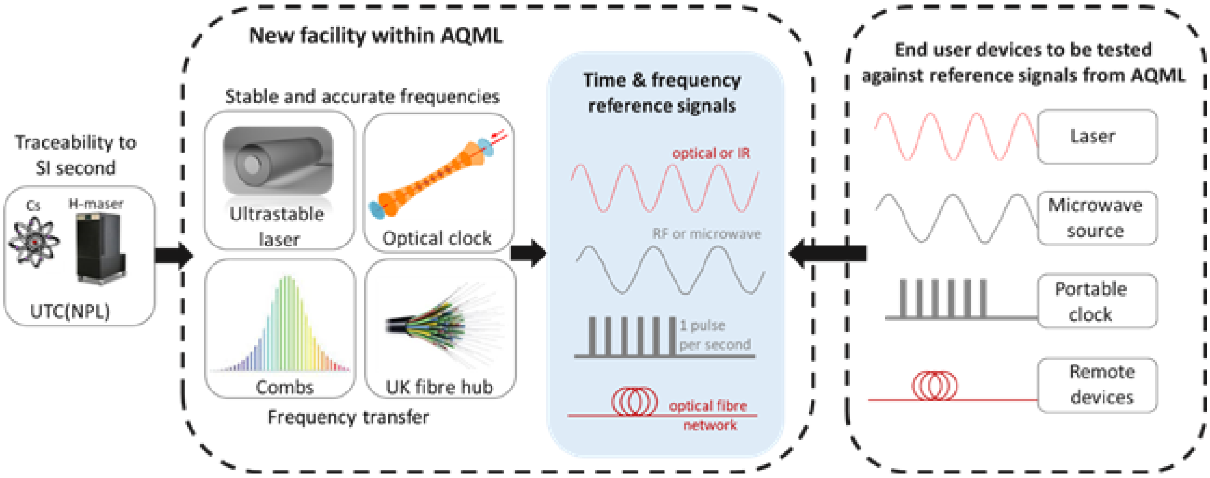

Figure 2. Dissemination of reference SI second signal for research purposes

In metrology field, NPL's Quantum metrology laboratories will realize the Quantum time and frequency standards and Quantum electrical measurements. NPL will also cover Quantum computing and Quantum communication technologies and will study on Quantum sensors, Quantum materials and characterization of compact lasers.

Quantum metrology studies, established under the auspices of the French National Metrology Institute LNE, will enable the implementation and dissemination of R&D studies on new generation quantum measurement standards and provide solutions to measurement needs related to the development of these technologies. In addition, standard and verified measurement and characterization tools and methods will be developed, traceability chains will be created and their implementation will be initiated. At the LNE Quantum Electric Metrology laboratory, they created a quantum electric current standard that is both universal and practical. To measure the Planck constant, researchers at LNE produced a Kibble balance (watt balance) to reveal the relationship between mechanical energy and electrical energy and thus create a mass standard. The system is based on the principle of measuring the change of the mass placed on one pan of the scale on a solenoid placed in the magnetic field on the other pan.

The Italian metrology institute INRİM has founded the Quantum metrology and nanotechnologies department and aims to create a metrological basis for quantum applications, photonics, atomic physics and nanotechnologies (INRİM, 2024).
INRİM will carry out the following activities:

- To carry out metrological research in the field of atomic clocks and to disseminate it to end users,
- Conducting scientific research and providing metrological reference for technologies based on quantum optics,
- Realization and maintenance of basic standards for electrical and radiometric units,
- Providing a time reference for Italy and contributing to the realization of the universal coordinated time (UTC) scale and International Atomic Time (TAI),
- To provide time reference for the European geolocation satellite network “Galileo”.

The Quantum Measurement Division (QMD) in National Metrology Institute (NIST) of USA provides the physical base for the International System of Units (Williams, 2017). The division was appointed in the redefinition of the SI and aims to achieve through precision measurements of various fundamental constants. Realization of resistance and voltage through the quantum Hall effect and Josephson Effect respectively, and through determination of the best values of the fundamental constants are responsibilities. NIST constructed a new Watt Balance which was used to make precise Planck constant measurements.

In the process of redefining units in the International System of Units (SI), Turkish national metrology institute TÜBİTAK UME Quantum Metrology Laboratory (QML) was established in 2018. Generation and characterization of resistance, voltage and current standards and creation of the "quantum metrological triangle" is intended in the established infrastructure. Additionally, "quantum dot thermometers" and "Coulomb blockade thermometers" will be produced and measured, and studies will be carried out in the fields of magnetism, optoelectronics, high frequency metrology and nanometrology (TÜBİTAK UME, 2024).

After new definition of SI mass, Kibble balance system as “National Kilogram Prototype” has been developed with a relative uncertainty of 2×10^{-8} as part of TÜBİTAK UME Quantum metrology program (Ahmedov et al., 2023; Ahmedov et al., 2018). Mass artefact turned into a Kibble balance system as seen in Figure 3.

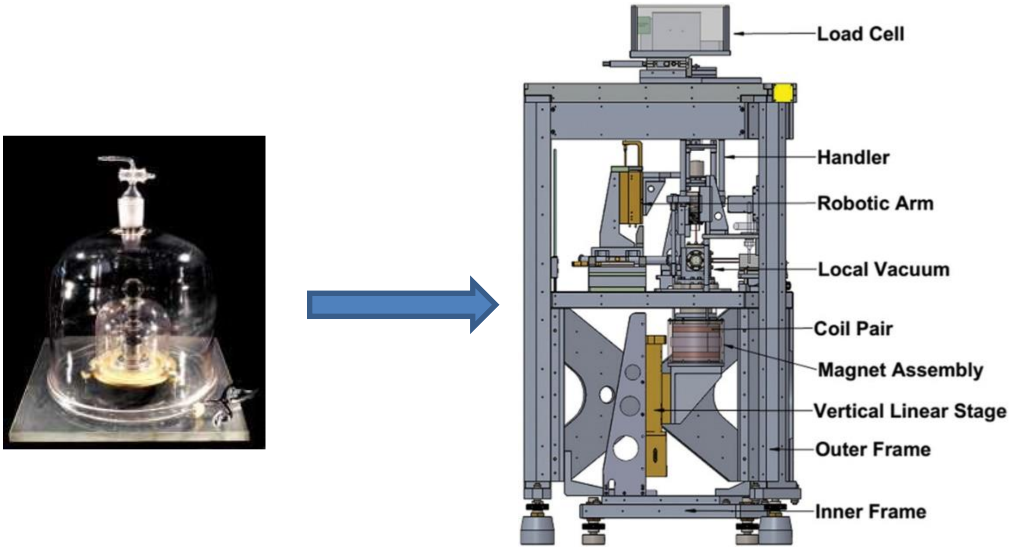

Figure 3. Mass artefact turned into a Kibble balance system

3. Discussions

3.1. Impact of SI New Definitions on Science

In general, new definitions in new SI units will lead to reduced uncertainties in our knowledge of many of the fundamental constants of physics, electricity, mechanics, and chemistry. The changes in the new SI will strengthen the philosophical basis of our system of units in relation to our current theoretical and understanding of quantum physics (Steele & Wood, 2020; Toro & Lehmann, 2021).

Defined constants range from fundamental constants of nature, such as the speed of light, c, to the technical constant such as Luminous efficacy of 540 THz radiation Kcd. Before 2019 h, e, k and N_A were not defined but instead were precisely measured quantities. In 2019 their values were fixed, ensuring continuity with previous definitions of the basic units, by definition according to the best estimates at the time. Defining the mole unit in chemistry has significant conceptual consequences. The exact and constant number of fundamental elements that define the mole unit will finally receive a proper definition and be called as Avogadro's number ($6.022\ 140\ 76 \times 10^{23}$). Important problems with artefact are, the possibility of disappearance, damage and changing its value, and the inability to change and adjust the possible errors.

There is now a critical mass of companies developing technologies that use quantum communications, for example, single photon detectors, quantum sensors supported by magnetic, temperature and pressure sensors. For example, single-photon confocal microscopes and quantum cameras based on quantum imaging are being developed (Barnes et al., 2018). The "Dimensional Metrology for Nanoscale Patterns" project carried out by the American National Metrology Institute (NIST) aims to measure critical dimensions at nm levels. Critical Size Small Angle X-ray

Scattering system can measure the pattern shape in nanostructure arrays in the range of 10 nm to 500 nm as can be seen in Figure 4 (NIST, 2024).

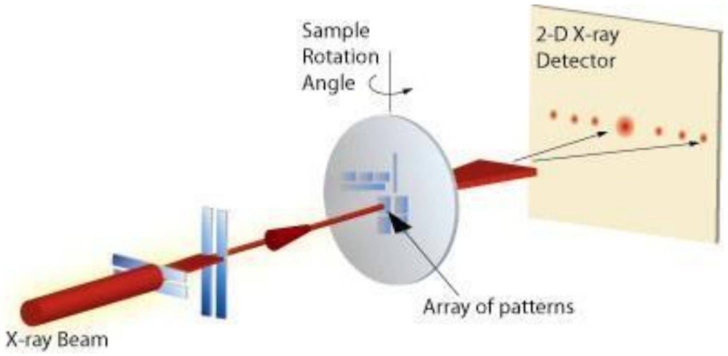

Figure 4. Critical Dimension Small Angle X-ray Scattering (CD-SAXS)

A start-up company has produced a microscope using the differential Hall Effect, which is innovative in metrology and based on quantum technology. It is a device built for depth profiling of electrical properties at atomic level resolution and automatic processing with direct data transfer as seen in Figure 5.

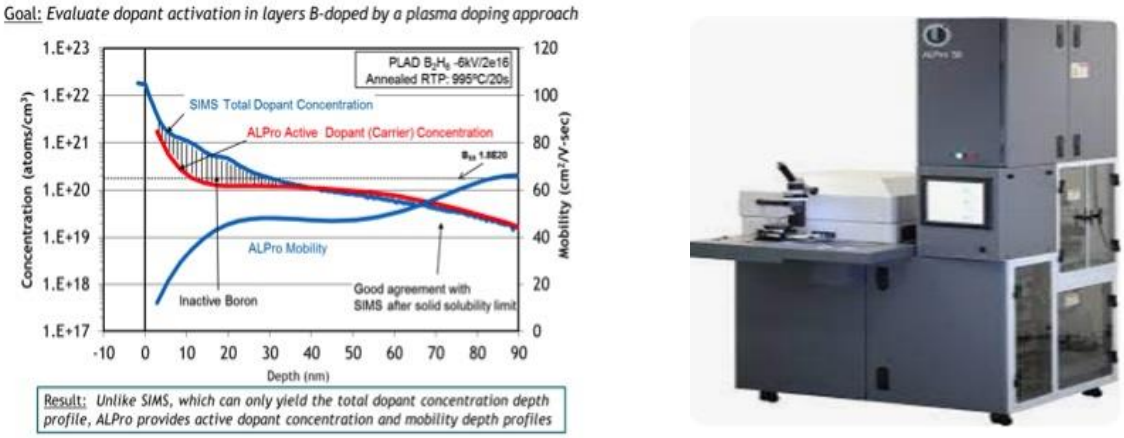

Figure 5. Differential Hall Effect

With the optical system in the quantum metrology approach, which enables the simultaneous determination of atomic dimensions, coating and film thickness, non-zero and zero-order refracted signals are captured from illuminated grating targets as well as from pattern-free regions of the surrounding substrate. Differential targets provide on-site dimensional calibration as seen in Figure 6 (Ausschnitt, 2004; Dorsch, 2018).

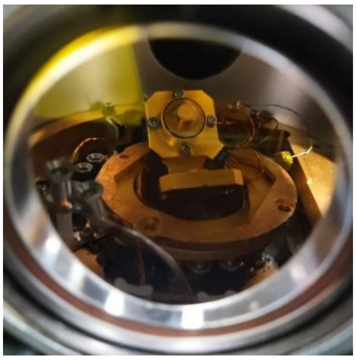

Figure 6. A New Approach to Pattern Metrology

The metrology institutes (INRIM and NPL) develop advanced research activities using optical-based and quantum-assisted measurements and quantum sensors. Institutes also form the metrological infrastructure necessary for the characterization and certification of quantum photonic devices.

Many superconducting microelectronic devices have been developed especially for metrology applications requiring high accuracy and sensitive advanced sensor technologies. Devices containing such sensors and technologies are already used in the fields of brain imaging and cosmology (VTT, 2024). Measurement of the physical properties of radiation and matter, which are among the main subjects of physics, is possible with quantum technology. The new metrological perspective in light of the revised units provides a deeper understanding of quantum measurements and ultra high-performance sensors (NQSTI, 2024). Advances in quantum technology are only possible with metrology. David Wineland and Serge Haroche, who demonstrated the "measurement and manipulation of individual quantum systems" of matter and light, were awarded the 2012 Nobel Prize in Physics. These are pioneering steps that led to the development of quantum computers and highly accurate optical clocks (Tzalenchuk et al., 2022).

4. Conclusions

Using metrology in scientific studies is necessary to capture the right perspective, improve knowledge and pave the way for innovation. The metrological perspective provides guidance that supports accurate measurements required in experiments and analyses. The quality and competence of scientific research depends on accurately measuring and quantifying material properties, particle behavior and the functioning of the complex world of nature. Metrology helps equip scientists with appropriate tools to develop precise measurement methods for cutting-edge technology. Whether determining the composition of a material, measuring the intensity of a signal, or measuring the rate of a chemical reaction, metrology allows researchers to determine data accurately and reliably. In scientific studies, measurements mean more than numbers. These are the building blocks by which theories are formulated and tested. The accuracy and validity of measurements directly affect the reliability and robustness of scientific findings (Toups, 2023).

It will take years for the new definitions of SI units to be implemented all over the world and for the changes to be actually implemented. However, it is important to plan how the communication and implementation of the revision will occur so that the changes are propagated to relevant areas. Although the proposed revision to SI units has been discussed in detail at the National Measurement Institutes (NMIs), it has been discussed more superficially in the industrial arena. Although the magnitude of changes in the revision of SI units is often too small to be visible to most industrial organizations, it is important to communicate why the change is being made, how it will occur, and what organizations must do to maintain traceability. It is essential to develop special metrological techniques to ensure the standardization and dissemination of new technologies in the light of innovations in science.

Declaration of Competing Interest and Ethics

The author declares no conflict of interest. This research study complies with research publishing ethics. The scientific and legal responsibility for this manuscript published in OPS Journal belongs to the author.

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