Chapter 2
International Harmonization of Measurements

Part I: International Measurement System

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Abstract The ***International System of Units (SI)*** of physical quantities is very important and necessary toolkit for any scientific development. The existing system adopted in 1960 by CGPM, France, is the globally well accepted, up-to-date, modern, coherent, having official status and even contemporary arrangement or form of the metric system starting with seven base units. It is almost dominant and globally accepted modern metric system of measurements used in science, engineering, technology, international trade and commerce. The system also embodied and agrees with limitless additional units, called derived units and special units, identified by special names and symbols which are always epitomized through seven base units. The SI is always envisioned to be an evolving system, wherein units, prefixes and definitions are created, modified and adapted as a result of international agreement arrived on the basis of advancement of measurement technologies and improvement in precision in measurements. As science evolves, advance technologies are developed which demand even more precise and accurate measurements. Due to advent of new technologies, the improvement in the accuracy of the products is carried out through development of new and improved measurement techniques, measurement standards and their definitions. Daily a number of precision measurements

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are performed which make our lives easier, comfortable, healthy and safer. In this chapter, authors have attempted to explain the historical aspects of metrology; international system of measurements, various international metrological organizations, for example, BIPM, NMIs, Metre Convention, MRA, etc. A brief overview of the importance and significance of the SI units; fundamental constants of nature (FCN) and their relevance in SI, historical aspects and evolution of SI units; redefinition of SI units in terms of FCN and current status and implication of redefined SI units, derived and other non-metric units, has also been presented. The whole contents are presented in a unique way to include scientific and analyzed data in tables, graphs, diagrams and flow charts to make the reading interesting for the readers.

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

– Lord Kelvin (1824-1907)

2.1 Introduction

It is well-known fact that metrology drives the growth engine of the any economy. No country can grow at its desired pace if metrology is ignored or not given due importance. The foundation of the metrology lies in the realization of SI units and a globally accepted uniform system of measurement. The current *International System of Units (SI)* is a very strong, universal, internationally well accepted, uniform, modern and lucid system, having official status. The existing arrangement or form of the metric system starts with realization of seven base units, which are now connected with nature's physical constants. The redefinitions of the seven base units are recently adopted and implemented. The system also embodied and agrees with limitless additional units, called derived units and special units, identified by special names and symbols. In this context, it is appropriate to review and describe the modern SI system, metrology, its significance, relevance and historical aspects.

2.2 Metrology and Measurement Systems

2.2.1 Introduction

Metrology plays a central role in scientific discoveries and innovation, industrial manufacturing and international trade, in improving the quality of life and in protecting the global environment. It not only provides the basis for the development of science and technology but also plays a vital role in our daily life. The economy of any state depends upon the manufacturing capability and global business which depends on international comparability of the manufactured products. Almost all aspects of the life including health, food, daily necessities, transportation, communication, business, economy, defence the measurements play key role. For global relevance of any society, international comparability of measurements is necessary. Incorrect measurements lead to wrong decisions, which can have serious consequences. Metrology helps to take logical judgments on the basis of uncertainty with the measurements of results and process. It also enhances confidence in the measurements and science behind it. Without the correct measurements, the ability to produce quality goods and fulfil consumer requirements would not be possible.

It is clear now that accurate and precise measurements are essentially required for better quality and confidence in the product. For ascertaining the accuracy and precision of a measurement, a calibrated reference standard is a must. For this, the measurement standards are developed, which not just only provide the reference for the measurement value but also provide the quality of measurements by stating the uncertainty related to the measurement. A better uncertainty is a proof, mark or evidence of the better quality of a measurement.

A user of any instruments should compare (calibrate) its instrument's measurement results with its respective measurement standard's results in order to judge the quality of its measurement by determining its uncertainty and hence the performance of the instrument. Now, this calibrated instrument can be used to calibrate another similar instrument or product in order to determine its quality but the only condition is that this chain of determining uncertainty should not be broken and ultimately traced to the national or international measurement standard. This unbroken chain of documented calibration with measurement uncertainty is known as *metrological traceability*. So any instrument used for measurement or producing final product/services should be traceable to measurement standard in order to obtain the required quality. If for a parameter, a measurement standard is not present, then certified reference material can be used as a reference for true measurement value. The national standards and certified reference materials are maintained by the *National Metrology Institute (NMI)* of the country.

Admittedly, metrology may not look very popular and crowd preferment but still it attracts the attention of experts and touches all walks of human life in almost all the socio, economic and industrial sectors. It plays a pivotal role as growth engine of industry for any country. It is an enabling tool for the development of technology, enhancing world-wide competence and building confidence. With the advent of better quality products through metrological advancement, our industries can compete globally, remove barriers and constraints in trade and commerce, boosting product demand and exports. This translates into growth for industries through rapid industrialization, economic growth and societal upliftment.

As an example, some of the metrological applications are described here. There are three main facets in *aerospace and automotive industry* for invention, creation, competitiveness and safety. Starting from a bike, cars to airplane, all rely upon metrology to keep their systems within certain quality parameters. In *automation and manufacturing sector*, nowadays, mostly manufacturing processing in plants is automated for control, monitoring, recording, production, quality checks by machines. Metrology plays a key role, in *energy and petrochemical* to cater the ever-increasing demand for more and more energy and petroleum products for keep on running the machines and the plants. In case of the *marine industry*, metrological instruments are used inside or outside of ships, tankers, vessels and much more. These are only few examples enough to signify the importance of metrology. It helps to create safe *environments and processes*, promotes innovation and increases knowledge and development.

As per *Vocabulary of Metrology (VIM)* document, metrology is defined as science of measurements and its applications. It includes all theoretical and practical aspects of measurement, whatever the measurement uncertainty and field of application [1]. It is often classified into *scientific or fundamental metrology, industrial or applied metrology* and *legal metrology*.

Scientific metrology is carried out mainly for compatibility of the measurements through research and development in the field of measurement standards, their maintenance and dissemination, is normally practiced at '*International Bureau of Weights and Measures (BIPM)*' and its associated organizations, specially NMI of the country. *Industrial metrology* is practiced for utility of measurements, including theoretical and practical, in manufacturing processes, ensuring the quality and accuracy of manufactured parts/components/products as well correctness of measuring instruments through test and calibration. Precise and accurate measurements improve the quality of the product, and therefore, support manufacturing and trade. *Legal Metrology* is performed for legitimacy of measurements with the statutory requirements concerning measurements as well as the law enforcement on measurements. These statutory requirements arise from a need for the protection of public health and safety, consumers rights, enabling taxation, the environment and fair trade are performed by competent bodies. In nutshell, legal metrology is responsible for improvement in quality of life. Figure 2.1 shows a simple diagram depicting conceptual classifications, specific purpose and applications of metrology in all the above three categories. For further details, please also refer Fig. 2.2.

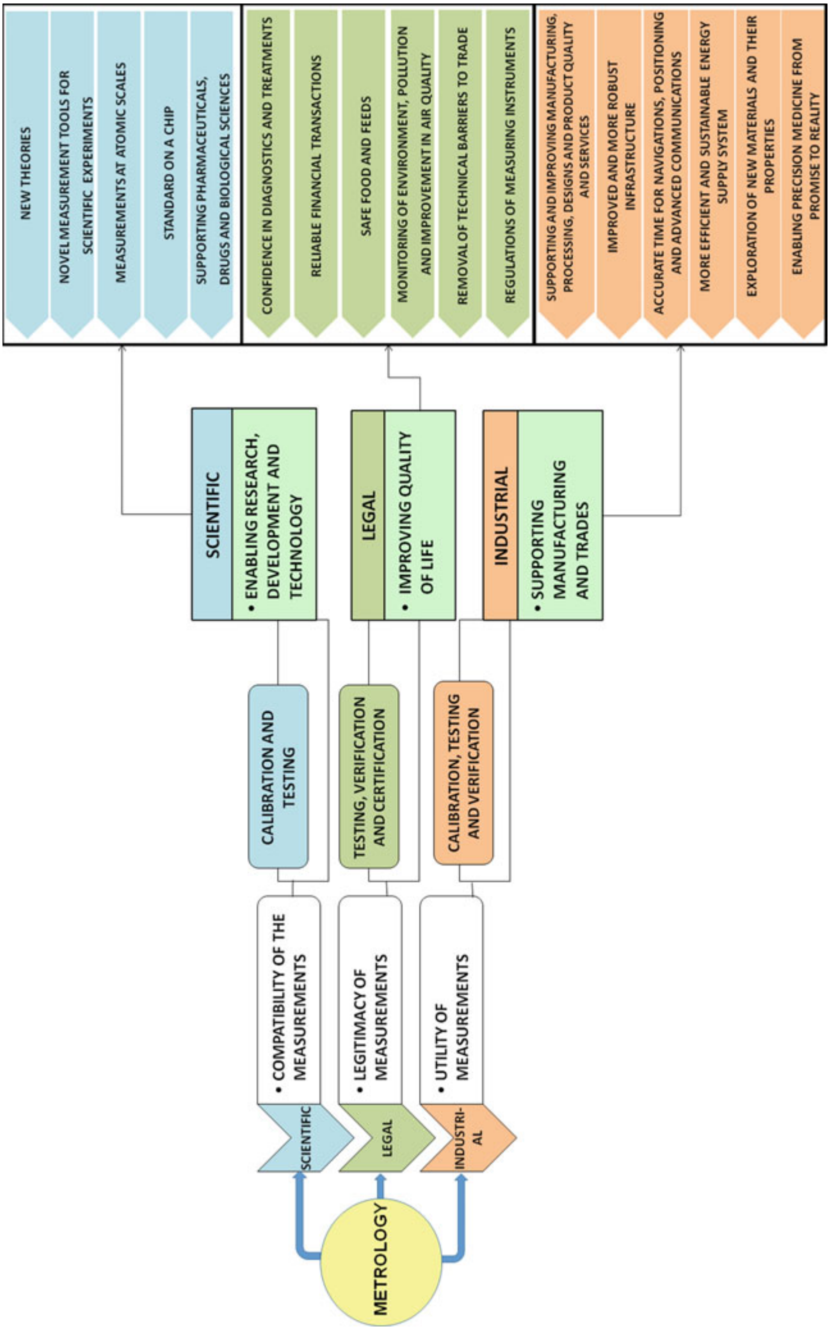


Fig. 2.1 Conceptual classifications and applications of scientific, legal and industrial metrology

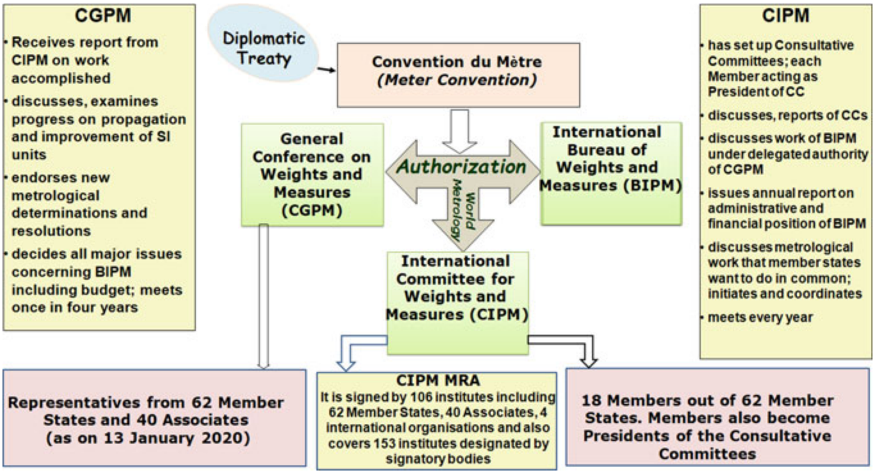


Fig. 2.2 Pictorial view of the hierarchy, interlinkages and main functions of BIPM, CGPM, CIPM and CIPM-MRA

2.2.2 Historical Aspects of Metrology

As a preliminary introductory point of view for the readers, the *property* of a phenomenon, body or substance, which can be expressed in terms of numbers, is defined as quantity, and the process of assigning a number to that property is termed as *measurement*, which facilitate the quantitative comparison of that property. Quantitative '*estimate*' is the value representing the measurement result. As a matter of fact, lot of science is involved in metrology including almost all the branches of science [1–3].

Life is about deal with physical world around us. Not only for human beings, but animals also, consciously and unconsciously, had been trying to quantify different things, such as food, distance to jump, for surviving. Even some of the animals use to mark their territory in forest, i.e. some sought of dimensions. Preparation of different type of nests by various types of birds, honeycomb are beautiful examples of quantification and measurements. With the progress of society, the demand of accurate measurements also increases side by side.

We live in the physical world, and feel 'space' and 'materials' around us. With the beginning of human civilization, and development of agriculture, the need of measurement of distribution of crops and the quantity of food were realized. After the age of nomadic groupings, when the humans started settling, measurements became important in managing population growth and agricultural food. Initially, measurements were based on natural things; hence, accuracy was not ascertained.

In the *most ancient age*, the great historic civilizations, China, India, Egypt, and Mesopotamia, were having the knowledge of metrology, since long back. In 1600 BC, using decimal metric system, China made archaeological discoveries, and the entire country was unified by spreading a uniform unit system. Egyptian pyramids are the witnesses of accurate dimensional metrology [4].

In the *middle ages*, to express their power, the different political authorities used to define units by their own. Hence, a large number of different units were defined differently for different goods, e.g. the weight pound was different for wheat and barley. In the nearby places of Paris, about forty-eight definitions for the measurement of surfaces existed during 1780 and long after that. Hence, the transactions for the unavoidable conversions required many cumbersome calculations [4].

For the social and ethical purposes, the field of measurement was intervened in the *French Revolution*. The need of uniform and simplified unit system was emphasized. For the simplifications in measurement and calculations, the use of decimal system was started. These simplifications resulted easier exchanges and hence increase in general welfare. The proposed reforms were adopted by other countries also. However, the goal to implement the revolutionary calendar, weeks of 10 days, hours of 100 min, and minutes of 100 s, could not be succeeded [4].

The development of scientific discoveries, the intensification of exchanges and the settlement of international institutions have been made during seventeenth to twenty-first century.

2.2.3 International Measurement System (IMS)

Due to regional and cultural variations in the different parts of the world, the systems of measurements were not consistent. For the progress of the society, the exchange and distribution of the knowledge is necessary. Due to lack of uniform measurement system and standards, the progress in scientific manner was not possible. The discovery of basic scientific laws and principles, such as electricity, magnetism and thermal physics, motivated to apply uniform standard of measurements around the world.

2.2.3.1 Introduction and Structure

The international system of measurement comprises of the globally accepted existing SI system and related activities and their operational mechanism through various intergovernmental and other international organizations on mutually agreed terms and conditions, Mutual Recognition Arrangements (MRAs) etc. A brief description of such operational mechanism is discussed in succeeding sections.

2.2.3.2 International Organizations and Their Operational Mechanism for IMS

Metre Convention and BIPM

After realizing the utmost need of global agreement on matters related to metrology, an international diplomatic treaty '*Metre Convention*' was established. The authorized government representatives of 17 countries signed the Convention on *20 May 1875* in Paris. The Convention set the framework for global collaboration in the science of measurement in its industrial, commercial and societal applications. In this treaty, an intergovernmental organization, 'BIPM' was established in Paris, France, through which *Member States* act together on matters related to measurement science and measurement standards. Although, at the time of signing *Metre Convention*, only 17 Member States participated; however, as of early 2020, the 62 Member States and 40 Associate States and Economies exist [5].

World Metrology Day

In view of ever-increasing relevance of global uniformity of measurements, the day 20 May 1875, on which '*Metre Convention*' was signed becomes very important. The *World Metrology Day (WMD)* is an annual celebration of the signature of the *Metre Convention* on 20 May 1875. The WMD was realized and initiated jointly by the BIPM and the International Organization of Legal Metrology (OIML). Every year, a theme is chosen to create awareness of the important role of measurements on different aspects of life, and a WMD Poster is releazed on that theme [6].

As stated very clearly on the website of the BIPM itself [7], the vision of the BIPM is 'to be universally recognized as the world focus for the international system of measurement'. With the mission, for the promotion and the advancement of global comparability of measurements, BIPM works with the RMOs and Member State's NMIs. This directly impacts the scientific discoveries, technological advancements, global trade and of course quality of life.

CGPM, CIPM and CIPM Mutual Recognition Arrangement (CIPM MRA)

BIPM operates under the direction and supervision of CIPM, which itself is under the authority of a '*General Conference on Weights and Measures (CGPM)*'. The CIPM consists of 18 members of different nationality. The appointing authority of the presidents of different *Consultative Committees (CCs)* is CIPM. The CIPM meetings are organized annually (since 2011 in two sessions per year). In the meetings, the reports submitted and presented by CCs are discussed. BIPM publishes the reports of the CGPM, CIPM and CCs meetings. The CIPM is mandated for the promotion of global uniformity in measurement units. CIPM discusses the work done by BIPM, and collaborative proposals from NMIs related to metrology research and activities, and after review make recommendations to CGPM.

CGPM, a supreme authority for all actions related to global metrology, is an intergovernmental conference participated by official delegates of Member States. Full Member States participate in all the BIPM activities, whereas Associate Member States are allowed to participate in the CIPM MRA programme only. Associate members have observer status at the CGPM.

Representing the global metrology community, BIPM is dedicated towards maximizing the impact of metrology on every important aspect of life, and developing opportunities for the application of metrology to global challenges. It makes liaison with other relevant intergovernmental organizations and international bodies and also provides an international platform for collaborative work related to metrology for Member States. It coordinates international comparisons of national measurement standards and establishes and maintains appropriate reference standards. The reference standards thus established are used for *International Key Comparisons* and also to provide calibrations for Member State's NMIs. As a coordinator of the worldwide measurement system, BIPM coordinates activities among the NMIs of Member States and the RMOs. It technically supports the CIPM MRA and the infrastructure for the development and promotion of the SI. To increase the effectiveness of the emerging metrology systems in the metrology community, BIPM also runs Capacity Building and Knowledge Transfer Programme [7].

A brief summary of the hierarchy, interlinkages and main functions of the diplomatic treaty, BIPM, CGPM, CIPM and CIPM MRA are shown in Fig. 2.2 and hierarchy of scientific, legal and industrial measurements performed world over in Fig. 2.3.

The CIPM, consisted of eminent metrologist and scientists of international community, is appointed by CGPM. It is responsible for the preparation and execution of the decisions made in CGPM. The reports submitted by CIPM to CGPM are passed to the governments and NMIs, the inputs received are examined and the proposals appropriate and related to changes to the SI units from the CIPM are approved. CIPM is also responsible for the supervision of the BIPM. Based on various core areas of metrology identified, the following 10 CCs are set up to assist CIPM [8]

CCAUV *Consultative Committee for Acoustics, Ultrasound and Vibration*
CCEM *Consultative Committee for Electricity and Magnetism*
CCL *Consultative Committee for Length*
CCM *Consultative Committee for Mass and Related Quantities*
CCPR *Consultative Committee for Photometry and Radiometry*
CCQM *Consultative Committee for Amount of Substance: Metrology in Chemistry and Biology*
CCRI *Consultative Committee for Ionizing Radiation*
CCT *Consultative Committee for Thermometry*
CCTF *Consultative Committee for Time and Frequency*
CCU *Consultative Committee for Units*

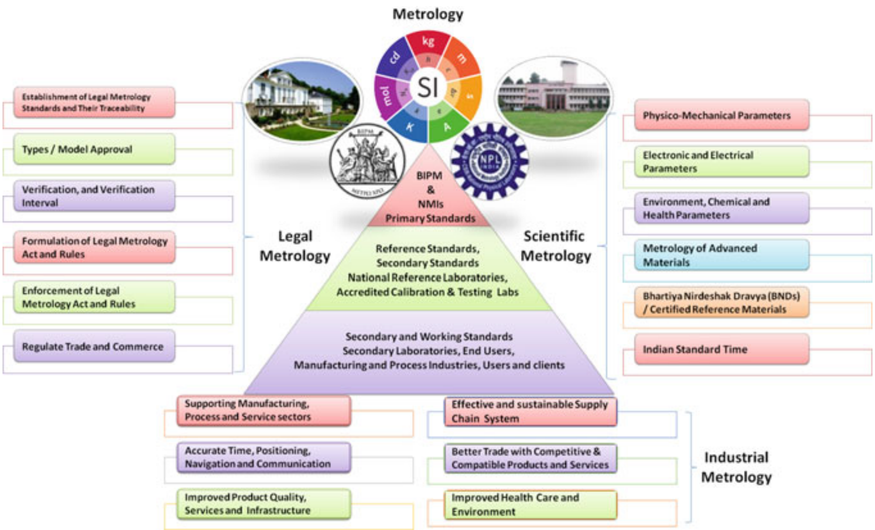


Fig. 2.3 Pictorial view of the hierarchy of scientific, legal and industrial measurements performed world over

The main motive of CCs is establishment of metrological traceability for related parameters to the SI, and hence, global comparability of measurements. Where traceability to SI is not possible; CCs make efforts for the establishment of internationally agreed reference standards. Hence, CCs play key role in implementation of CIPM MRA, and its maintenance, which contributes in establishment of globally recognized metrological standards, methods and measurement systems.

The CCs in their respective areas discuss all the matters that make impact on metrology and other scientific activities organized by BIPM and advise to CIPM accordingly. CCs also review the calibration and measurement services of BIPM including uncertainties in measurements and advice CIPM accordingly. CCs are the platforms for discussion among members and observers, regarding metrology and collaboration.

The President of the respective committee, in general, chairs respective CC meetings, also usually works as a member of the CIPM. NMIs from the Member States that are active in the field, but lack the expertise to become members, are able to attend the CC meetings as observers. The CCU advises on the matters related to the development of the SI. It works in association with other relevant international bodies, e.g. *International Organization for Standardization (ISO), International Astronomical Union (IAU), International Union of Pure and Applied Chemistry (IUPAC) and International Union of Pure and Applied Physics (IUPAP).* The SI brochure, which contains formal definitions of the SI units, is produced by the CCU in conjunction with a number of other international organizations. The most recent 9th edition of SI brochure was published in 2019 [9].

In general, all the member countries/economies, participating in international metrology programmes, designate a Scientific Institute at National Level, as NMI, e.g. *National Institute of Standards and Technology (NIST) in USA, National Physical Laboratory (NPL) in UK, The Physikalisch-Technische Bundesanstalt (PTB) in Germany*, etc. The NMIs are the custodian of national level primary and secondary standards, and responsible to disseminate the metrological traceability of SI units to respective country. The directors of the NMIs participate in the meetings organized by BIPM, in which the global concerns related to metrology are discussed. The government representatives of Member State's government representatives can also participate in these meetings.

For demonstrating the international acceptability, equivalence of the measurement standards and the calibration and measurement certificates issued by NMIs, CIPM MRA was established. It was signed by the representatives of one hundred and six institutes of sixty-two numbers of Member States, forty numbers of associate members of CGPM and four numbers of international organizations. It also covers one hundred and fifty-three numbers of institutes designated by members and other signatories [10].

CMCs, Key Comparisons, Peer Review, Global Equivalence, RMOs and KCDB

The CIPM MRA results are globally recognized as *Calibration and Measurement Capabilities (CMCs)* of signatory and other participating members. Approved CMCs are publicly available in the *Key Comparison Database (KCDB)* on the BIPM website. CMCs are stated in terms of a measurand and its uncertainty, and may include advice about the instrumentation used. The operation of an appropriate and approved quality management system; participation in reviewed and approved intercomparisons; and international *Peer Review* of claimed measurement capabilities, are necessary for approval and publication of CMCs [11].

To facilitate the ease of participation of different countries in the international metrological activities organized by BIPM, and representation in CCs, RMOs were established [12]. RMOs work within the framework of the CIPM MRA.

For getting set of results for measurement of any parameter for CIPM MRA, key comparisons are conducted by CCs, BIPM and RMOs. The results of these key comparisons are published and maintained in the KCDB. Only NMIs or *Designated Institutes (DIs)* of Member States, who have highest level of technical competency, participate in key comparisons. These comparisons provide '*the reference value*' for the quantity for which comparison was conducted. Whereas RMO key comparisons are organized at regional level, and metrology laboratories of Member States and also associates can participate in the comparisons. The comparisons organized by RMOs provide complementary information, however, with no change in the reference value. The development of the CMCs depends on the results of key comparisons.

CMC is available to customers under normal conditions; (i) as published in the BIPM KCDB of the CIPM MRA; and (ii) as described in the laboratory's scope,

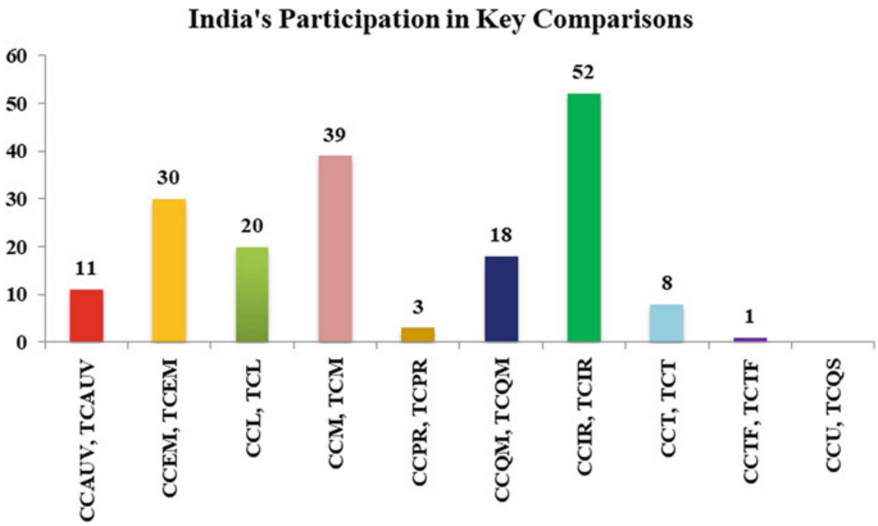
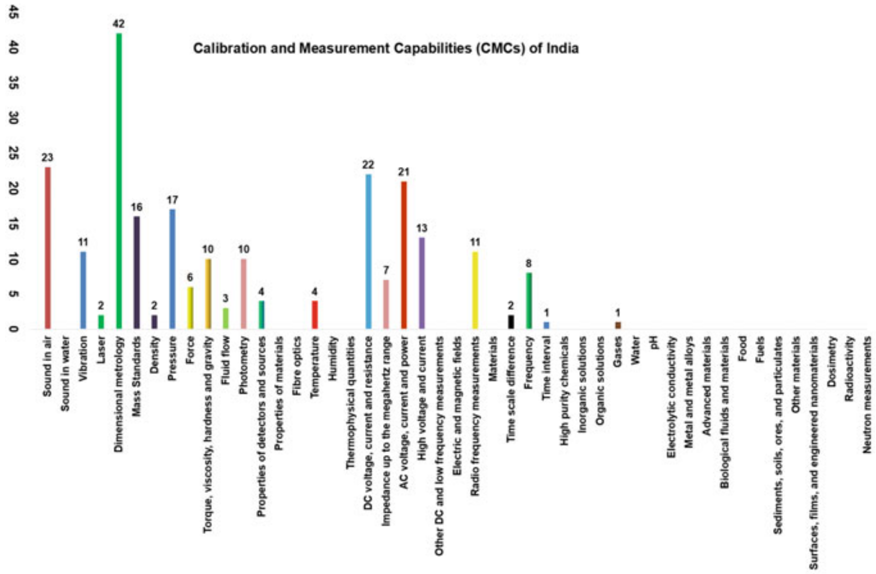


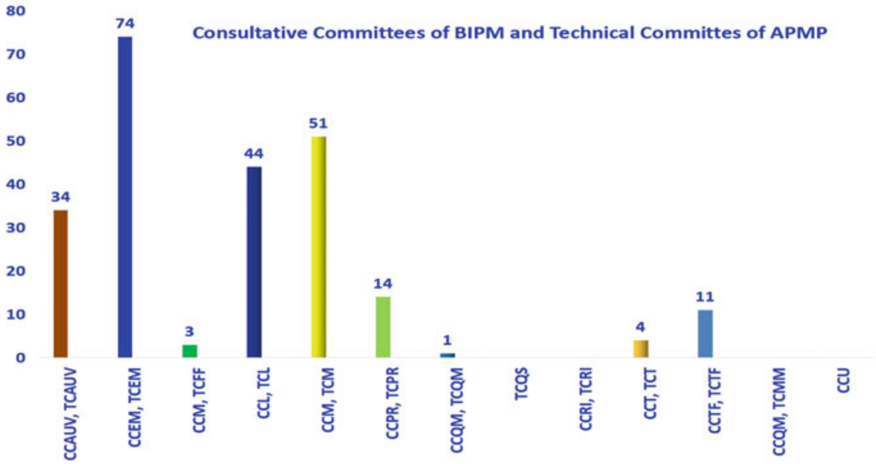
Fig. 2.4 Successful Indian participation in key comparison exercises. CCU and TCQS are shown only as representation of the CC and TC. However, these committees do not participate in any key comparison, and accordingly, no key comparison is shown against their names

duly implemented through the *Quality Management System (QMS)* as per ISO/IEC 17025 standard, and approved through a 'Peer Review' process in the laboratory's scope through the accreditation granted by a accreditation body as signatory to the ILAC MRA. The CMCs, developed by the participants, are submitted through their RMOs for Peer Review. Once the process of Peer Review is successfully completed, the RMOs submit the CMCs for second stage interregional review process. After completion of both the review processes successfully, the CMCs are published in KCDB, through *Joint Committee of the RMOs and the BIPM (JCRB)*. The CSIR-NPL, being NMI of India and *Bhabha Atomic Research Centre (BARC)* as DI for ionization radiation, have successfully participated in 182 key comparison exercises as shown in Fig. 2.4.

After approval and publication of CMCs in KCDB, the metrology institutes can use CIPM MRA logo in the calibration and measurement certificates, which make the certificate recognition, by all other signatories of the CIPM MRA. To conduct intercomparisons within, the region is the major task of RMOs. Before publishing approved CMCs in the KCDB, RMOs, through JCRB, carry out an interregional review of declared measurement capabilities. RMOs also make suggestions to the CIPM regarding policy of operation of the CIPM MRA. After rigorous exercises of key comparisons and Peer Review processes, India has published total of 236 CMCs in the KCDB over the years as shown in Fig. 2.5a for parameter wise and Fig. 2.5b under various CCs and *Technical Committees (TCs)* of RMOs.



(a)



(b)

Fig. 2.5 Indian CMCs published in KCDB, **a** parameter wise and **b** as per organization by CCs and TCs. CCU and TCQS are shown only as representation of the CC and TC. However, no CMC is published by these committees, and accordingly, no CMC is shown against their names

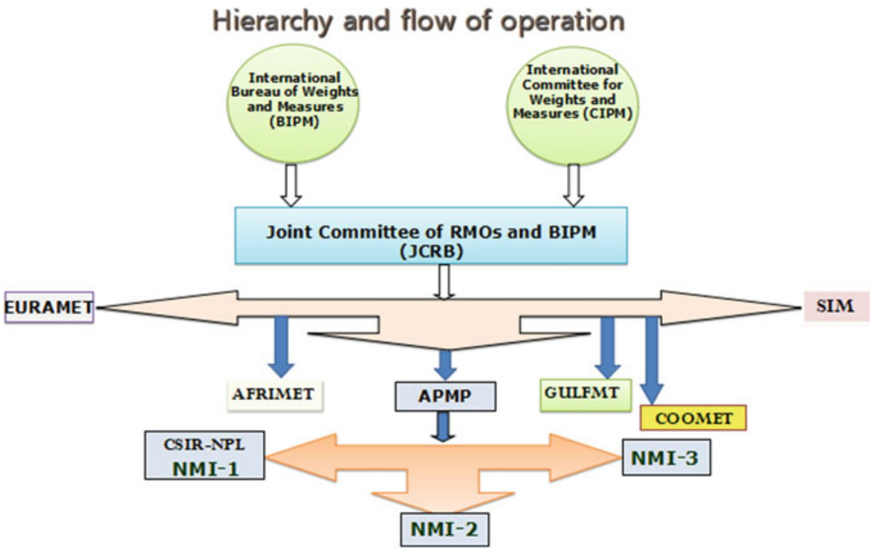


Fig. 2.6 A flow diagram showing linkages and operations between RMOs, NMIs, BIPM and CIPM

Making proposals to the CCs regarding key comparisons; carrying out the RMO key comparisons, participation in the JCRB; carrying out supplementary comparisons, supporting mutual confidence in the measurement capabilities of participating institutes are the key responsibilities of RMOs. The hierarchy and flow of operations of RMOs with NMIs, CIPM and BIPM are depicted in Fig. 2.6. Currently, following six RMOs are recognized within the framework of the CIPM MRA:

Intra-Africa Metrology System (AFRIMETS);

Asia Pacific Metrology Programme (APMP);

Euro-Asian Cooperation of National Metrological Institutions (COOMET);

European Association of National Metrology Institutes (EURAMET);

Gulf Association for Metrology (GULFMET);

Inter-American Metrology System (SIM).

For particular tasks of common interest of BIPM and other international organizations, a number of Joint Committees were formed [13]: (i) *JCGM: Joint Committee for Guides in Metrology*, for maintaining and promoting the use of the *'Guide to the Expression of Uncertainty in Measurement (GUM)'* and the 'International Vocabulary of Basic and General Terms in Metrology (VIM)'. (ii) *JCRB: Joint Committee of the Regional Metrology Organizations and the BIPM*, for coordinating the activities among the RMOs in establishing confidence for the mutual recognition of certificates of measurements in the purview of CIPM MRA. It also makes policy suggestions to the RMOs, analyze the application of RMOs for CIPM MRA, analyze the proposals of each RMO for CMCs of member NMIs and report to the CIPM, facilitate appropriate interregional supplementary comparisons, and finally write annual report on the activities of the Joint Committee to the CIPM and to the signatories of the CIPM MRA. (iii) *JCTLM: Joint Committee for Traceability in Laboratory Medicine*, for responding to the need of establishing lists of available higher-order reference materials, available higher-order reference measurement procedures and reference measurement laboratories for laboratory medicine. (iv) *JCTLM Executive Committee, JCTLM Database WG for Reference Materials, Procedures and Measurement Laboratories, JCTLM WG on Traceability for Education and Promotion on Traceability in Laboratory Medicine.*

2.3 International System of Units (SI)

2.3.1 Introduction of SI Units

The International System of Units (Système international in french) abbreviated as SI is the system of measurement which has an official status, and adopted by almost all the countries. SI is formed of coherent system of seven base units, and twenty-two derived units represented in the form of multiplication of the power of the base units and given special names and symbols. These base and derived units form as much as other derived units to express large numbers of quantities. To express multiples, sub-multiples of the units, twenty prefixes to the unit names and symbols are used. Based on the need of the time and the scientific and technological advancements, SI is continuously evolving system, in which the definitions are also modified through international consensus and agreement. Since the adoption of the system, the efforts are being made to make the system independent from the effect of physical factors and time, and hence, the base units are being defined in terms of universal or fundamental constants rather than artefact. In 2019, all the SI units have been defined by fixing the numerical values for seven defining constants when expressed in terms of their SI units [14]. The current section of the chapter comprises of the historical evaluation and development of the SI system, current status, fundamental constants, derived units, dissemination of the units at national level.

2.3.2 Historical Aspects and Evaluation of SI Units

The most necessary measurement in life is ‘*length*’. Initially, the units of length or distance were defined in reference to King’s thumb and foot and pace, as ‘inch’, ‘foot’ and 'yard', respectively. The mile was defined as 'thousand paces'. The unit 'cubit' was defined as length of forearm between elbow to tip of middle finger. However, due to inconsistency in the body parts of the kings, more consistent standardization was needed. The standardization of the 'cubit' was done in a royal master cubit made of black marble (~52 cm). The standard cubit was divided into 28 digits (about finger width), and further fractions resulted the smallest unit of millimetre (mm) [15].

Another next most important quantity in human life is '*weight*'. Due to wide variations in the weight of humans, it was not practical to define weight in reference to human body. Initially, weight of standard size of grains was considered as unit. For example, 'carat' (quirat in Arab) was the seed of the coral tree, which has now been standardized as 0.2 g. The lump of metal corresponding to given number of grains had been considered as standard [16].

One of the related quantity '*volume*' was standardized using baskets, sacks or pottery jars of consistent sizes. The counts of seed of plants filled in certain capacity vessels were used for measurement of volume. The unit used for volume in ancient Egyptians time was 'hen' nearly equal to present day 477 cm^3 [16].

For understanding dynamic process and variations, '*time*' was defined. Initially, the units of time were defined in terms of solar cycle, e.g. day, week, month and year. In the day, the time was divided with respect to position of the Sun. Further, the concept of hours, minutes and seconds was developed [16].

With the progress in human civilization, as per need, the relatively consistent devices were developed for the measurements of above mentioned quantities. The relatively more consistent measurement of time was done by examining the position of the shadow of vertical stick of given length. However, due to variations in the position of sun in different seasons, this technique needed improvements. The flow of sand or fluid from pan of given volume through hole of given dimension was another device to measure time in more consistent manner [16].

In the first-century AD, a technique for the surveying of land using plotting of relative position of features in a landscape was developed. Concept of angles was used in such measurements. The technique was further improved for the measurement of angle of stars.

In fourteenth century, concept of clock dividing the day in forenoon and after noon having twelve hours in each segment was introduced. In fourteenth—sixteenth century, the hour was further subdivided in terms of minutes and seconds [16].

In seventeen century, the concept of atmospheric pressure and barometer for pressure measurement was discovered. After the need of quantification of the warmness, and conceptualization of the physical quantity '*temperature*', efforts towards measurement of 'temperature' were started. In 1650, Gabriel Daniel Fahrenheit designed an alcohol-filled glass thermometer. Further, the performance of liquid in glass thermometer was improved by filling the Hg in place of alcohol. Further, the freezing point and boiling point of water were used for scaling of the thermometer [16].

At the time of the French Revolution, the metric system was created, and further on 22 June 1799, the two platinum standards for the unit of length and mass were made, which laid down the foundation of present SI system [17].

In 1832, using the metric system, for the first time, Gauss did absolute measurements of the Earth's magnetic field in terms of a decimal system based on the three units millimetre, gram and second. A further electrical phenomenon was also added in these measurements. In 1860, with the base and derived units, the need of the coherent system of units was formulated by Maxwell and Thomson. Both of them worked through the British Association for the Advancement of Science (BAAS). In 1874, the centimetre, gram, second (CGS) system was introduced by the BAAS. In the CGS system, the prefix for representing the decimal and multiples from micro to mega were also introduced. In 1880s, a mutually coherent set of units ohm, volt and ampere (for electrical resistance, electromotive force and electric current, respectively) was approved by the BAAS and the International Electrical Congress [predecessor of the International Electrotechnical Commission (IEC)] [17].

After the Metre Convention, the new international prototypes for the 'metre' and the 'kilogram' were established in the 1st CGPM in 1889. Together with the astronomical second, these units created the metre, kilogram, second (MKS) system. By adding a fourth unit of an electrical nature 'ampere' in 1901, a coherent four-dimensional system was formed, which opened the path to a number of new developments [17].

In the 6th CGPM held in 1921, the Metre Convention was revised, and the four-dimensional MKSA system based on metre, kilogram, second and ampere, was approved and adopted in 1946. In 1948, the 9th CGPM instructed the CIPM to get the opinion and suggestions of scientific, technical, academic stakeholder for establishment of a practical system of units useful for all the signatories of Metre Convention, and to study about establishment of a complete set of rules for units of measurement. The 'general principles for the writing of unit symbols' were also laid down by CGPM. In addition, some coherent derived units were assigned special names [17].

In the 10th CGPM (1954), the kelvin and the candela, as base units for thermodynamic temperature and luminous intensity, respectively, were also incorporated in base units. The name International System of Units was abbreviation as SI, in 11th CGPM (1960). In 1971, in the 14th CGPM, the seventh base unit, the mole, was adopted for the quantity amount of substance [17].

From then, the extraordinary advances in SI units have been started. Full efforts to define SI units in terms of invariant quantities such as the fundamental constants of physics and the properties of atoms were started. In 2011, in the 24th CGPM, the principles of a new definition of the SI base unites were adopted. A set of seven constants was identified as references for the definitions. At that time, the experimental determine of the values of these constants in terms of base units was not completely consistent. Till 2018, it was achieved, and in the 26th CGPM (2018), the new definitions of the SI were approved and adopted [17].

2.3.2.1 Unit of Length, Metre

In 8 May 1790, it was decided by the French National Assembly that the units of the physical quantities should be defined in terms of basic physical principles, and the definition of the metre was proposed as the length of a pendulum with a half-period of one second. In 30 March 1791, the French Academy of Sciences proposed a new definition for the metre as one ten millionth of the length of a great circle quadrant along the Earth's meridian through Paris, that is the distance from the equator to the north pole along that quadrant, which was accepted by the French National Assembly. In 1795, a length bar made of brass was considered as standard for metre. In 1799, the platinum metre bar was deposited in the National Archives, as the final standard.

After the Metre Convention, in 1889, the 1st CGPM defined 'the metre as the distance between two lines on a standard bar of an alloy of platinum with 10% iridium, measured at the melting point of ice'. In 1927, 7th CGPM redefined the metre as the distance, at 0 °C (273 K), between the axis of the two central lines marked on the prototype bar of platinum–iridium, this bar being subject to one standard atmosphere of pressure and supported on two cylinders of at least 10 mm (1 cm) diameter, symmetrically placed in the same horizontal plane at a distance of 571 mm (57.1 cm) from each other. To avoid artefact-based realization of unit, in 1960, the 11th CGPM redefined the metre in terms of a certain number of wavelengths of a certain emission line of krypton-86. The metre is 1650763.73 wavelengths in a vacuum of the radiation corresponding to the transition between the $2p^{10}$ and $5d^5$ quantum levels of the krypton-86 atom. In 1983, the 17th CGPM defined the metre as the length of the path travelled by light in a vacuum during a time interval of 1/299,792,458 of a second. The definition was based on fundamental constant, velocity of light in vacuum '*c*'. In order to harmonize with the definitions of the other units, and to make clear its dependence on the fixed numerical value of the speed of light, *c*, the wording of the definition was changed in the 26th CGPM (2018) [17].

2.3.2.2 Unit of Mass, Kilogram

In 1793, the kilogram was defined as the mass of 1 litre (dm^3) of water, which was determined to be 18841 grains. In 1795, the 1000th part of kilogram, the unit gram was provisionally defined as the mass of one cubic centimetre of water at the melting point of ice. In 1799, an artefact prototype for kilogram was manufactured. After signing the 'Metre Convention', in 1879, the IPK was prepared, which was adopted in 1889. It had a mass equal to the mass of 1 dm^3 of water under atmospheric pressure and at the temperature of its maximum density, which is approximately 4 °C. In order to assure universality of the unit of mass, a new definition for the kilogram based on the value of a fundamental Planck' constant was adopted by the 26th CGPM in 2018 [17].

2.3.2.3 Unit of Time, Second

Before 1960, the unit of time, the second, was defined as the fraction 1/86,400 of the ‘mean solar day’. However, rotation of the Earth measured to be irregular. Hence, to improve the definition, in 1960, the 11th CGPM adopted a definition based on the tropical year 1900. However, experimental studies on atomic and molecular transitions proved that the atomic frequency standard can be realized and reproduced much more accurately. Considering that the 13th CGPM has chosen a new definition of the second in 1967 terms of the frequency of the ground-state hyperfine transition in the caesium 133 atom. In 2018, 26th CGPM approved a revised and more precise statement of the same definition, in terms of a fixed numerical value of the unperturbed ground-state hyperfine transition frequency of the caesium 133 atom, $\Delta\nu_{Cs}$ [17].

2.3.2.4 Unit of Electric Current, Ampere

In 1893, the units for the electrical parameters current and resistance were introduced by the International Electrical Congress, and the definitions of the ‘international ampere’ and ‘international ohm’ were introduced in 1908. In 1948, the 9th CGPM approved the definition of the ampere, the force between parallel wires carrying an electric current and it had the effect of fixing the numerical value of the vacuum magnetic permeability μ_0. The numerical value of the vacuum electricpermittivityε_0 then became fixed as a consequence of the new definition of the metre adopted in 1983. After facing difficulties in the realization of the ampere, and subsequent advancement in electrical quantum standards of voltage and resistance, based on Josephson and quantum Hall effects, which are linked through Ohm’s law, the ampere was realized in terms of volt and ohm. The volt and the ohm are realized using combinations of the Planck constant (h) and elementary charge (e). As a consequence, it became natural not only to fix the numerical value of h to redefine the kilogram, but also to fix the numerical value of e to redefine the ampere in order to bring the practical quantum electrical standards into exact agreement with the SI. In 2018, 26th CGPM adopted the definition of ampere based on a fixed numerical value for the elementary charge, e [17].

2.3.2.5 Unit of Thermodynamic Temperature, Kelvin

In 1954, 10th CGPM approved the triple point of water (TPW) as a fundamental fixed point by assigning it the temperature 273.16 K, for defining the ‘kelvin’, the unit of thermodynamic temperature. In 1967-68, the 13th CGPM adopted the name ‘kelvin’, symbol K, instead of ‘degree kelvin’, symbol °K. The practical realization required a sample of pure water of well-defined isotopic composition that is material and process dependent. The technological advancements in the field of thermometry motivated to realize the ‘kelvin’ in terms of Boltzmann constant k. In 2018, the 26th

CGPM approved the definition of unit kelvin by fixing the numerical value of the k [17].

2.3.2.6 Unit of Luminous Intensity, Candela

Prior to 1948, the units of luminous intensity were based on flame of specific candle or illumination of incandescent filament standards. Further, the unit of luminous intensity 'new candle' was defined in reference to the luminance of a Planckian radiator (a black body) at the temperature of freezing platinum. In 1948, 9th CGPM adopted the name 'the candela', symbol 'cd' for the units of luminous intensity. In 1954, it was established as a base unit. In 1967, the 13th CGPM amended this definition. After technological advancements in the field of detector-based absolute radiometry, in 1979, the candela was redefined in reference to the human eye response. In 2018, 26th CGPM adopted the definition of candela based on fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd} [17].

2.3.2.7 Unit of Amount of Substance, Mole

The quantity 'amount of substance' (n) is used to specify the amount of chemical elements or compounds. This is defined to be proportional to the number of specified elementary entities N in a sample, and the proportionality constant is a universal constant for all entities. The proportionality constant is the reciprocal of the Avogadro constant N_{A}, so that $n = N/N_{\mathrm{A}}$. The unit of amount of substance is called the 'mole'. Based on the proposals of the IUPAP, IUPAC and ISO, in 1969, the CIPM confirmed the definition of mol, by specifying that the molar mass of C-12 as exactly 0.012 kg/mol. The definition of the mole was dependent on the artefact definition of the kilogram. The N_{A} defined here was equal to the number of atoms in12 grams of C-12, and the precise knowledge of N_{A} was not required in the realization of 'mol' [17].

After continuous technological advancements during decades, the N_{A} is now known with fairly high precision and can be used to define mole. Hence, mole can be defined by specifying the exact number of entities in one mole, i.e. by fixing the numerical value of the N_{A}. In result, the definition of mole and the N_{A} need not to depend on definition of the 'kilogram'. Thus, now the difference between fundamentally distinct quantities 'mass' and 'amount of substance' can be emphasized.

In 2018, 26th CGPM adopted the definition of the mole based on a fixed numerical value for the Avogadro constant, N_{A} [17].

2.3.3 Fundamental Constants of Nature (FCN)

To achieve the universal consistency in SI, in 2011, it was proposed to define SI fully in terms of natural constants. In 2017, the updated values of the constants were published. In November 2018, members of sixty nations unanimously voted for the change of SI in terms of fundamental/natural constants. On 20 May 2019, at the occasion of the '*World Metrology Day*', the revised SI was implemented. Since May 2019, all of the SI base units have been implemented in terms of physical constants.

A physical quantity, having constant value irrespective of time and space, is called fundamental constant of nature or universal constant. The speed of light in vacuum 'c', the gravitational constant 'G', the Planck constant 'h', the electric constant 'ε_0', and the elementary charge 'e' are some of the well-known examples of physical constants. The term 'physical constant' does not refer to a numerical value, whereas only physical quantity. Numerical values of the dimensional physical constants are dependent upon the system of units used to express. The physical quantities regarded as immutable and non-derivable from more fundamental principles are termed as 'fundamental physical constant', e.g. c and G. Fixed quantities of any desired dimension can be defined by combining dimensional universal physical constants [18].

The revised SI rests on a foundation of seven values, known as the constants. The values of the constants are the same everywhere in the universe. In the revised SI, these constants completely define the seven base SI units, from the second to the candela [14].

As a result, the constants: the speed of light in vacuum (c), the Planck constant (h), the elementary charge (e), the Avogadro constant (N_A), and the Boltzmann constant (k), have known exact numerical values when expressed in SI units.

The c, h and e are fundamental constants. The speed of light in vacuum 'c' is the limit of speed in the universe and nothing can travel faster than light. The Planck constant 'h' is one of the fundamental constants of quantum physics, which establishes the relation between energy and frequency of light quanta. This also limits the measurement accuracy of two complementary physical quantities simultaneously by Heisenberg uncertainty principle. The elementary charge 'e' is the amount of charge in an electron.

The N_A and k are the technical constants. They give a proportionality factor for defining the units used. The k relates energy to its temperature, and appeared along with the absolute temperature in almost all the physical laws and principles. The N_A defines the number of particles in a mole.

The time is defined in terms of the hyperfine transition frequency of caesium 133 ($\Delta\nu_{Cs}$). Caesium 133 is a metal atom. The energy of Cs outermost electron can be controlled with microwave radiation. The frequency of microwave radiation that causes this electron to jump between two closely spaced low-energy states is known as the hyperfine transition frequency.

The *candela* is defined in terms of the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, denoted as K_{cd}, which is related to human eye

Table 2.1 Information about defining constants [14]

Defining constant	Numerical value
Hyperfine transition frequency of caesium 133 ($\Delta\nu_{Cs}$)	9 192 631 770 Hz
Speed of light in vacuum (c)	299 792 458 m s^{-1}
Planck constant (h)	6.626 070 15 × 10^{-34} J s
Elementary charge (e)	1.602 176 634 × 10^{-19} C
Boltzmann constant (k_B)	1.380 649 × 10^{-23} J K^{-1}
Avogadro constant (N_A)	6.022 140 76 × 10^{23} mol^{-1}
luminous efficacy of monochromatic radiation of frequency 540 × 10^{12} Hz (K_{cd})	683 lm W^{-1}

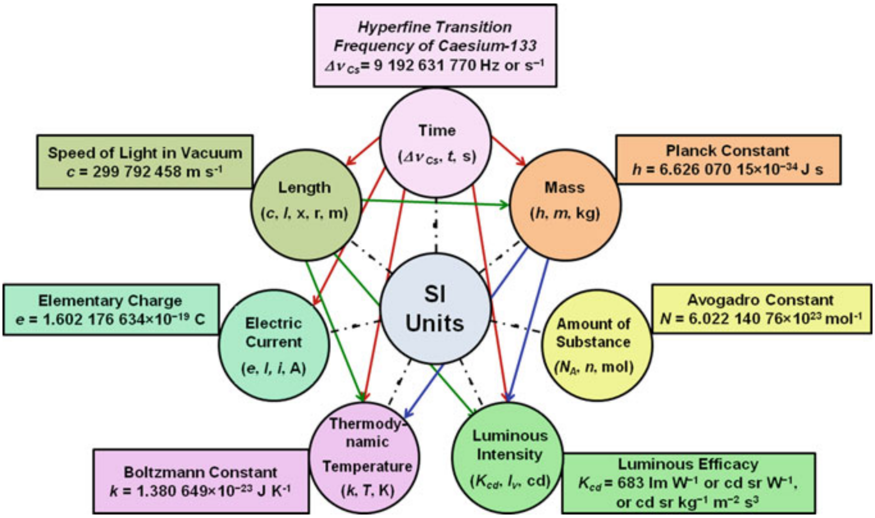


Fig. 2.7 Seven SI base units, relation with each other and their defining constants

response. 'luminous efficacy' is the total amount of visible light (sensed by human eye) produced by a light source using a certain amount of power. Information about the defining constants is included in Table 2.1 and about seven base units in Fig. 2.7.

2.3.4 Redefinition of SI Units in Terms of FCN and Current Status

The redefinition of SI based units in terms of fixed numerical values of the defining constants, effective from 20 May 2019, reproduced in Table 2.2, as published in Resolution 1 of 26th CGPM [19]:

Table 2.2 Redefinition of seven SI base units and their expressions [20]

SI base unit and symbol	Definition
second, s	The **second**, symbol **s**, is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency $\boldsymbol{\Delta\nu_{Cs}}$, the unperturbed **ground-state hyperfine transition frequency of the caesium-133 atom**, to be 9 192 631 770 when expressed in the unit Hz, which is equal to $s^{-1.}$
	This definition implies the exact relation $\Delta\nu_{\mathrm{Cs}} = 9\ 192\ 631\ 770$ Hz. Inverting this relation gives an expression for the unit second in terms of the defining constant $\Delta\nu_{\mathrm{Cs}}$: $1\mathrm{Hz} = \frac{\Delta\nu_{\mathrm{Cs}}}{9\,192\,631\,770}$ or $1\mathrm{s} = \frac{9\,192\,631\,770}{\Delta\nu_{\mathrm{Cs}}}$ The effect of this definition is that the second is equal to the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the unperturbed ground state of the ^{133}Cs atom
metre, m	The **metre**, symbol **m**, is the SI unit of length. It is defined by taking the fixed numerical value of the **speed of light in vacuum *c*** to be 299 792 458 when expressed in the unit ms^{-1}, where the second is defined in terms of $\Delta\nu_{\mathrm{Cs}}$
	This definition implies the exact relation $c = 299\ 792\ 458\ \mathrm{m\ s}^{-1.}$ Inverting this relation gives an exact expression for the metre in terms of the defining constants c and $\Delta\nu_{\mathrm{Cs}}$: $1\mathrm{m} = \left(\frac{c}{299\,792\,458}\right)\mathrm{s} = \left(\frac{9\,192\,631\,770}{299\,792\,458}\right)\frac{c}{\Delta\nu_{\mathrm{Cs}}} \approx 30.663\,319\frac{c}{\Delta\nu_{\mathrm{Cs}}}$ The effect of this definition is that one metre is the length of the path travelled by light in vacuum during a time interval with duration of 1/299 792 458 of a second
kilogram, kg	The **kilogram**, symbol **kg**, is the SI unit of mass. It is defined by taking the fixed numerical value of the **Planck constant *h*** to be $6.626\ 070\ 15 \times 10^{-34}$ when expressed in the unit J s, which is equal to kg $\mathrm{m}^2\ \mathrm{s}^{-1}$, where the metre and the second are defined in terms of c and $\Delta\nu_{\mathrm{Cs}}$
	This definition implies the exact relation $h = 6.626\ 070\ 15 \times 10^{-34}\ \mathrm{kg\ m^2\ s^{-1}}$. Inverting this relation gives an exact expression for the kilogram in terms of the three defining constants h, $\Delta\nu_{Cs}$ and c: $1\ \mathrm{kg} = \left(\frac{h}{6.626\,070\,15 \times 10^{-34}}\right)\mathrm{m}^{-2}\ \mathrm{s}$ which is equal to: $1\ \mathrm{kg} = \frac{(299\,792\,458)^2}{(6.626\,070\,15 \times 10^{-34})(9\,192\,631\,770)}\frac{h\Delta\nu_{\mathrm{Cs}}}{c^2} \approx 1.475\,521\,4 \times 10^{40}\frac{h\Delta\nu_{\mathrm{Cs}}}{c^2}$ The effect of this definition is to define the unit kg $\mathrm{m}^2\ \mathrm{s}^{-1}$ (the unit of both the physical quantities action and angular momentum). Together with the definitions of the second and the metre, this leads to a definition of the unit of mass expressed in terms of the Planck constant h
ampere, A	The **ampere**, symbol **A**, is the SI unit of electric current. It is defined by taking the fixed numerical value of **the elementary charge *e*** to be $1.602\ 176\ 634 \times 10^{-19}$ when expressed in the unit C, which is equal to A s, where the second is defined in terms of capital $\Delta\nu_{\mathrm{Cs}}$

(continued)

Table 2.2 (continued)

SI base unit and symbol	Definition
	This definition implies the exact relation $e = 1.602\ 176\ 634 \times 10^{-19}$ A s. Inverting this relation gives an exact expression for the unit ampere in terms of the defining constants e and $\Delta\nu_{Cs}$: $1\ \mathrm{A} = \left(\frac{e}{1.602\,176\,634 \times 10^{-19}}\right)\mathrm{s}^{-1}$ which is equal to: $1\ \mathrm{A} = \frac{1}{(9\,192\,631\,770)(1.602\,176\,634 \times 10^{-19})}\Delta\nu_{\mathrm{Cs}}e \approx 6.789\,6868 \times 10^{8}\Delta\nu_{\mathrm{Cs}}e$ The effect of this definition is that one ampere is the electric current corresponding to the flow of $1/(1.602\ 176\ 634 \times 10^{-19})$ elementary charges per second.
kelvin, K	The **kelvin**, symbol **K**, is the SI unit of thermodynamic temperature. It is defined by taking the fixed numerical value of the **Boltzmann constant** $\boldsymbol{k}$ to be $1.380\ 649 \times 10^{-23}$ when expressed in the unit J K^{-1}, which is equal to kg $\mathrm{m}^2\ \mathrm{s}^{-2}\ \mathrm{K}^{-1}$, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{\mathrm{Cs}}$
	This definition implies the exact relation $k = 1.380\ 649 \times 10^{-23}$ kg $\mathrm{m}^2\ \mathrm{s}^{-2}\ \mathrm{K}^{-1}$. Inverting this relation gives an exact expression for the kelvin in terms of the defining constants k, h and $\Delta\nu_{\mathrm{Cs}}$: $1\ \mathrm{K} = \left(\frac{1.380\,649}{k}\right)10^{-23}\mathrm{kg\ m^2 s^{-2}}$ which is equal to: $1\mathrm{K} = \frac{(1.380\,649 \times 10^{-23})}{(6.626\,070\,15 \times 10^{-34})(9\,192\,631\,770)}\frac{\Delta\nu_{\mathrm{Cs}}h}{k} \approx 2.266\,6653\frac{\Delta\nu_{\mathrm{Cs}}h}{k}$ The effect of this definition is that one kelvin is equal to the change of thermodynamic temperature that results in a change of thermal energy k T by $1.380\ 649 \times 10^{-23}$ J
mole, mol	The **mole**, symbol **mol**, is the SI unit of amount of substance. One mole contains exactly $6.022\ 140\ 76 \times 10^{23}$ elementary entities. This number is the fixed numerical value of the **Avogadro constant,** $\boldsymbol{N_{\mathrm{A}}}$, when expressed in the unit mol^{-1} and is called the Avogadro number The amount of substance, symbol n, of a system is a measure of the number of specified elementary entities. An elementary entity may be an atom, a molecule, an ion, an electron, any other particle or specified group of particles
	This definition implies the exact relation $N_{\mathrm{A}} = 6.022\ 140\ 76 \times 10^{23}\ \mathrm{mol}^{-1}$. Inverting this relation gives an exact expression for the mole in terms of the defining constant N_{A}: $1\ \mathrm{mol} = \left(\frac{6.022\,140\,76 \times 10^{23}}{N_A}\right)$ The effect of this definition is that the mole is the amount of substance of a system that contains $6.022\ 140\ 76 \times 10^{23}$ specified elementary entities
candela, cd	The **candela**, symbol **cd**, is the SI unit of luminous intensity in a given direction. It is defined by taking the fixed numerical value of the **luminous efficacy** of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd}, to be 683 when expressed in the unit lm W^{-1}, which is equal to cd sr W^{-1}, or cd sr $\mathrm{kg}^{-1}\ \mathrm{m}^{-2}\ \mathrm{s}^{3}$, where the kilogram, metre and second are defined in terms of h,c and $\Delta\nu_{Cs}$

(continued)

Table 2.2 (continued)

SI base unit and symbol	Definition
	This definition implies the exact relation $K_{cd} = 683$ cd sr kg^{-1} m^{-2} s^{3} for monochromatic radiation of frequency $\nu = 540 \times 10^{12}$ Hz. Inverting this relation gives an exact expression for the candela in terms of the defining constants K_{cd}, h and $\Delta\nu_{Cs}$: $1\text{cd} = \left(\frac{K_{cd}}{683}\right)\text{kg m}^2\text{s}^{-3}\text{sr}^{-1}$ Which is equal to $1\text{ cd} = \frac{1}{(6.626\,070\,15 \times 10^{-34})(9\,192\,631\,770)^2 683}(\Delta\nu_{Cs})^2 h K_{cd} \approx 2.614\,8305 \times 10^{10}(\Delta\nu_{Cs})^2 h K_{cd}$ The effect of this definition is that one candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} Hz and has a radiant intensity in that direction of (1/683) W/sr

A unique way is proposed to represent the redefinitions in a common format as written in first row of the (Table 2.3), in which after filling the respective information of different SI units given in the seven rows can help in understanding and remember the definitions of seven base units. As definition of 'mol' is slightly different, which is written separately.

After the linkages with the other defined units like second, metre, kilogram, these can be represented to express the dimensional quantities. The metre–kilogram–second and ampere as the core units and the candela–kelvin–mole as the non-core SI units, as depicted in Fig. 2.8 [21]. This effort results into the simpler and more fundamental representation of the entire SI. They are now artefact free definitions, particularly the international prototype of kilogram for mass and isotopic composition dependent triple point of water for kelvin.

2.3.5 Implication of Redefined SI Units

In the Sect. 2.3.3, we have described the fundamental constants of nature (FCN) and how they are used to redefine the SI base units. The unanimous historic decision was made in 26th CGPM on the redefinition of four of the base units of; kilogram, kelvin, ampere and mole by fixing the numerical values of Planck constant, Boltzmann constant, elementary charge and Avogadro constant, respectively. These fundamental constants are inherently stable. Therefore, FCNs have been chosen so that the revised definitions need not be modified again in foreseeable time to accommodate future improvements in the technologies used to realize the base units.

Table 2.3 The harmonized redefinitions of the base units are attempted to be represented in a common format, as given in the first row of the table. The definition of any base unit can be written by filling the blanks by the information given in front of the base unit in the respective row. As definition of 'mol' is slightly different, which is written separately [20]

The … (SI base unit name), symbol … (symbol of SI base unit name), is the SI unit of … (name of base quantity)
It is defined by taking the fixed numerical value of the … (name and symbol and the description of defining constant), to be … (value of the defining constant)
when expressed in the unit … (unit of the defining constant), which is equal to … (unit of defining constant in terms of SI units), where …(relevant SI base units with respective defining constants for representing respective base unit)

SI base unit name	SI base unit symbol	Name of SI base quantity	Name and symbol, and description of defining constant	Value of the defining constant	Unit of the defining constant	In terms of SI base units	Relevant SI base units with respective defining constants for representing respective base unit
second	s	time	caesium frequency $\Delta\nu_{Cs}$, the unperturbed ground-state hyperfine transition frequency of the caesium 133 atom	9 192 631 770	Hz	s^{-1}	
metre	m	length	speed of light in vacuum, *c*	299 792 458	$m\ s^{-1}$		the second is defined in terms of the caesium frequency $\Delta\nu_{Cs}$

(continued)

Table 2.3 (continued)

The … (SI base unit name), symbol … (symbol of SI base unit name), is the SI unit of … (name of base quantity)
It is defined by taking the fixed numerical value of the … (name and symbol and the description of defining constant), to be … (value of the defining constant)
when expressed in the unit … (unit of the defining constant), which is equal to … (unit of defining constant in terms of SI units), where …(relevant SI base units with respective defining constants for representing respective base unit)

SI base unit name	SI base unit symbol	Name of SI base quantity	Name and symbol, and description of defining constant	Value of the defining constant	Unit of the defining constant	In terms of SI base units	Relevant SI base units with respective defining constants for representing respective base unit
kilogram	kg	mass	Planck constant, h	$6.626\ 070\ 15 \times 10^{-34}$	J s	kg m^2 s^{-1}	the metre and the second are defined in terms of c and $\Delta\nu_{Cs}$

(continued)

Table 2.3 (continued)

The … (SI base unit name), symbol … (symbol of SI base unit name), is the SI unit of … (name of base quantity)
It is defined by taking the fixed numerical value of the … (name and symbol and the description of defining constant), to be … (value of the defining constant)
when expressed in the unit … (unit of the defining constant), which is equal to … (unit of defining constant in terms of SI units), where …(relevant SI base units with respective defining constants for representing respective base unit)

SI base unit name	SI base unit symbol	Name of SI base quantity	Name and symbol, and description of defining constant	Value of the defining constant	Unit of the defining constant	In terms of SI base units	Relevant SI base units with respective defining constants for representing respective base unit
ampere	A	electric current	elementary charge, e	$1.602\ 176\ 634 \times 10^{-19}$	C	A s	the second is defined in terms of the caesium frequency $\Delta\nu_{Cs}$

(continued)

Table 2.3 (continued)

The … (SI base unit name), symbol … (symbol of SI base unit name), is the SI unit of … (name of base quantity)
It is defined by taking the fixed numerical value of the … (name and symbol and the description of defining constant), to be … (value of the defining constant)
when expressed in the unit … (unit of the defining constant), which is equal to … (unit of defining constant in terms of SI units), where …(relevant SI base units with respective defining constants for representing respective base unit)

SI base unit name	SI base unit symbol	Name of SI base quantity	Name and symbol, and description of defining constant	Value of the defining constant	Unit of the defining constant	In terms of SI base units	Relevant SI base units with respective defining constants for representing respective base unit
kelvin	K	thermodynamic temperature.	Boltzmann constant, k	$1.380\,649 \times 10^{-23}$	$\mathrm{J\,K^{-1}}$	$\mathrm{kg\,m^2\,s^{-2}\,K^{-1}}$	the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{Cs}$
candela	cd	luminous intensity in a given direction	luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd}	683	$\mathrm{lm\,W^{-1}}$	$\mathrm{cd\,sr\,W^{-1}}$, or $\mathrm{cd\,sr\,kg^{-1}\,m^{-2}\,s^3}$	the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{Cs}$

(continued)

Table 2.3 (continued)

The … (SI base unit name), symbol … (symbol of SI base unit name), is the SI unit of … (name of base quantity)
It is defined by taking the fixed numerical value of the … (name and symbol and the description of defining constant), to be … (value of the defining constant)
when expressed in the unit … (unit of the defining constant), which is equal to … (unit of defining constant in terms of SI units), where …(relevant SI base units with respective defining constants for representing respective base unit)

SI base unit name	SI base unit symbol	Name of SI base quantity	Name and symbol, and description of defining constant	Value of the defining constant	Unit of the defining constant	In terms of SI base units	Relevant SI base units with respective defining constants for representing respective base unit
mole	mol	amount of substance	One mole contains exactly $6.022\ 140\ 76 \times 10^{23}$ elementary entities. This number is the fixed numerical value of the Avogadro constant, N_A, when expressed in the unit mol^{-1} and is called the Avogadro number The amount of substance, symbol n, of a system is a measure of the number of specified elementary entities. An elementary entity may be an atom, a molecule, an ion, an electron, any other particle or specified group of particles.				

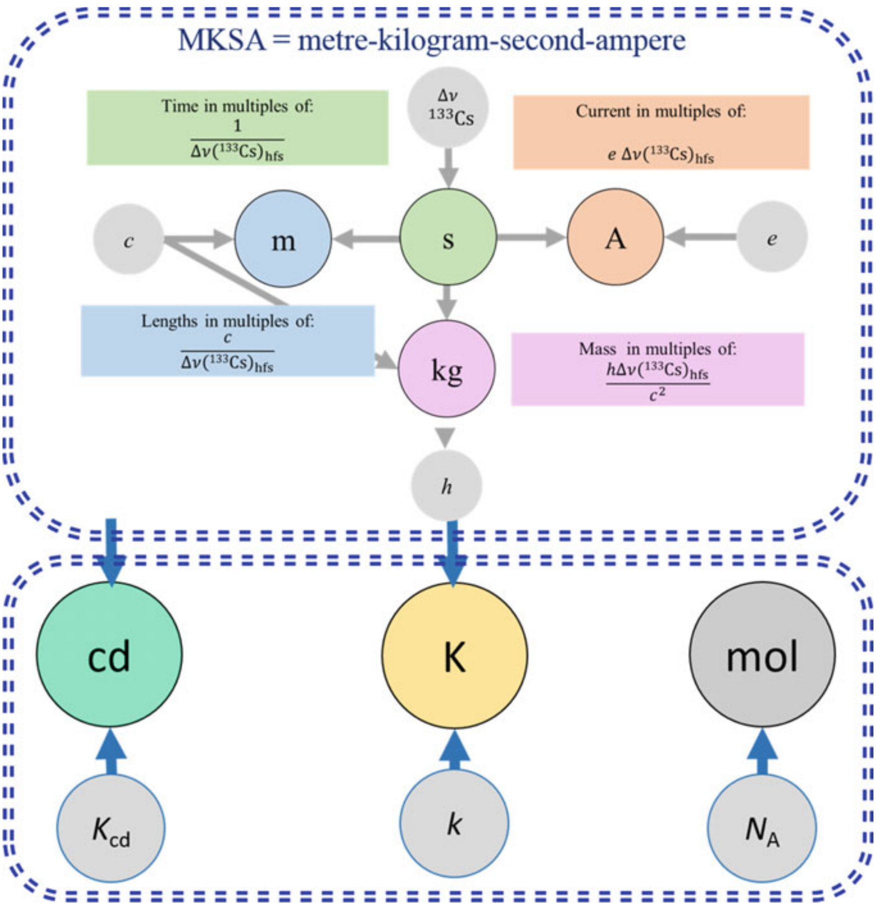


Fig. 2.8 Illustrating the SI base units in core and non-core unit groups depending on their usages in expressing the dimensionality of quantities for other SI and derived units [21]

2.3.5.1 The Robustness of Fundamental Constants Used for New SI

It is the understanding and the belief of the scientific community that the fundamental constants such as c, h and e have not changed for a long time. The search for the variation of fundamental constants is always motivated by the theories unifying the fundamental interactions such as fine structure constant (α) and the proton-to-electron mass ratio (μ).

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{hc} \tag{2.1}$$

where the stability of α can be measured using the high precision atomic clocks of relative uncertainties of 10^{-16} and even below in terms of frequency ratio. Four fundamental constants related to four SI base units are involved in Eq. 2.1. The 2014 tests on experimental stability of α were found to be $-0.7 \pm 2.1 \times 10^{-17}$ per year for NPL(UK) results and $-2.0 \pm 2.0 \times 10^{-17}$ per year for PTB, Germany results [22, 23], respectively.

The future progress in time will see even more robust consistency in these measurements with the direct measurements of optical frequency ratios than the caesium atomic clock. This suggests that the α is one million times more stable than the kilogram mass. Therefore, redefinition of SI units by fixing their numerical values is robust and will not affect any technological development in near future. This motivated for the linkages of the major of the redefined SI units with the unit of time, the second. The revolutionary advancements in atomic physics and quantum metrology, in past 50 years, have enabled the definitions of the second and metre, and the practical realization of electrical units with unprecedented accuracy. Here, the definitions of the SI units of the second, the metre and the candela are also rephrased in 2018, as presented in the following section.

Before fixing the values of the fundamental constants, the well-defined conditions of concerned CCs and CCU have been satisfied by the results obtained till 1st July 2017. These results were then summarized and the CODATA 2017 [24] values of fundamental constants were published and used for the redefinitions of units.

2.3.5.2 The Implementation of Redefined SI Based Units

The traceable measurements are the quantitative comparison of an unknown quantity with standard quantity. Historically, most of the definitions of standard units were also part of its realization and dissemination. Traditionally, it includes some part of their preferred mode of realizations. If we separate the definition from realization, we allow realization to evolve over decades in the ways we cannot anticipate. Say, for example, the IPK was part of the realization and dissemination of mass. The unit definition of ampere was abstract or idealized, where magnetic effect of current was a measure. However, the ampere was being realized using the Quantum Hall Resistance and Josephson voltage standards.

In the new SI, the realizations are separated conceptually from the definitions so that the units based on fundamental constants can be realized independently at any place and at any time. Mise-in-pratique (MeP) [25] for each of the redefined SI unit has been given with the available methods of primary standards for the realization and dissemination. There is no single preferred method. In addition to above, with the development of science and technology, several new and advantageous realization methods shall be developed and introduced in future, without any need to redefine the unit. It can be clearly visualized from the historical developments happened with the definition of SI metre, it transformed from Pt–Ir artefact to atomic reference transition to present definition of fixed numerical value of the speed of light, led to

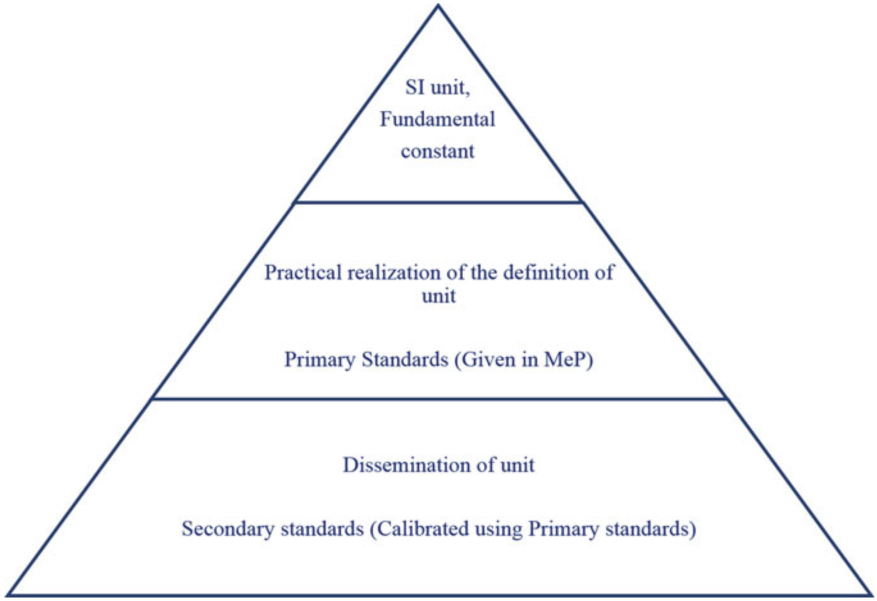


Fig. 2.9 Illustration of the traceability chain from the definition of SI unit

the decision to define all units by using defining constants. Figure 2.9 illustrates the traceability chain from the definition of SI unit

2.3.5.3 The Implications of Redefined SI Based Units

As mentioned earlier, the revised definitions are based on seven fundamental physical constants (e.g. the Planck constant, the Boltzmann constant, the elementary charge and the Avogadro constant) and are therefore inherently stable. Most common users outside the NMIs will not notice the change, and implications will be evolved through the process of realizations and dissemination over the coming years. The relevant mise-en-pratique has been published describing the methods for the practical realizations of the new definitions at NMIs. Some information about how these changes might affect the different areas of measurement and the implications of redefinitions, is given below, reproduced from the 'practical realizations of the definitions of some important units' BIPM website and published literature [25–29].

The Kilogram Defined in Terms of the Planck Constant (*h*)

- The **kilogram** is now defined in terms of the Planck constant (*h*), guaranteeing long-term stability of the SI mass scale. The *h* has an unprecedented realization uncertainty of 9.1 × 10^{-9} by Kibble balance at NRC Canada, before fixing its value for the redefinition.

- The kilogram can be realized by any suitable primary method, as described in MeP, such as the *Kibble (watt) balance* or the *X-ray crystal density method (XRCD)* method used for Avogadro constant, where *h* is calculated using the Bohr model of the hydrogen atom.
- IPK at the time of redefinition is 1 kg exactly; however, NMIs need not have to necessarily get the traceability from BIPM, if the *h* is realized with above primary methods. The realization uncertainty of *h* about ±10 μg will be added to the uncertainty of the IPK and correspondingly at the CMC of copy of IPK at respective NMIs [30].
- The substitution values of mass realized by primary methods, such as few mg, μg can be set as primary, instead of 1 kg.
- Users can also continue to obtain traceability to the SI from the same sources used as before through the BIPM, national metrology institutes and accredited laboratories. International comparisons will ensure their consistency.
- There was no change in the SI kilogram at the time of redefinition, to maintain the consistency to previous measurements.
- The uncertainties given by NMIs to their calibration customers will be mostly unaffected. The traceability chart for the redefined kilogram is shown in Fig. 2.10.

The Ampere Defined in Terms of Elementary Charge (*e*)

- The ampere and other electrical units are practically realized at the highest metrological level and consistent with the definitions.
- The determination of elementary charge was calculated from experimental values of fine structure constant α, *h* and *c* and μ_0. The *CODATA* value thus fixed has the relative standard uncertainty of 5.2 × 10^{-9}.
- As per MeP, the unit ampere can be realized in three ways; (i) by using *Ohm's law*, the unit relation $A = V/\Omega$, using the SI derived units the volt V and the ohm Ω, based on the Josephson and quantum Hall effects, respectively; (ii) by using a *single electron transport (SET)* or similar device, the unit relation $A = C/s$, the value of e given in the definition of the ampere and realized second s; and (iii) by using the relation $I = C{\cdot}\mathrm{d}U/\mathrm{d}t$, the unit relation $A = F{\cdot}V/s$, with volt V and the farad F and of the SI base unit second s.
- With the reassessment of *h* and *e*, the effect on the practical realization of volt and resistance, involving Josephson constant and von Klitzing constants, associated relative uncertainty would be approximately of the order of 19 × 10^{-9} and 22 × 10^{-9}, respectively. These changes would be visible to NMI level users and would be most unaffected for majority of users.
- SET has higher uncertainty now, but it is a most appropriate method for the realization of *e*, and expected to improve with the advent of technology.
- The revised SI has resulted in small changes to all other disseminated electrical units, say because of the resultant adjustments in K_J and R_K, because of the fixing

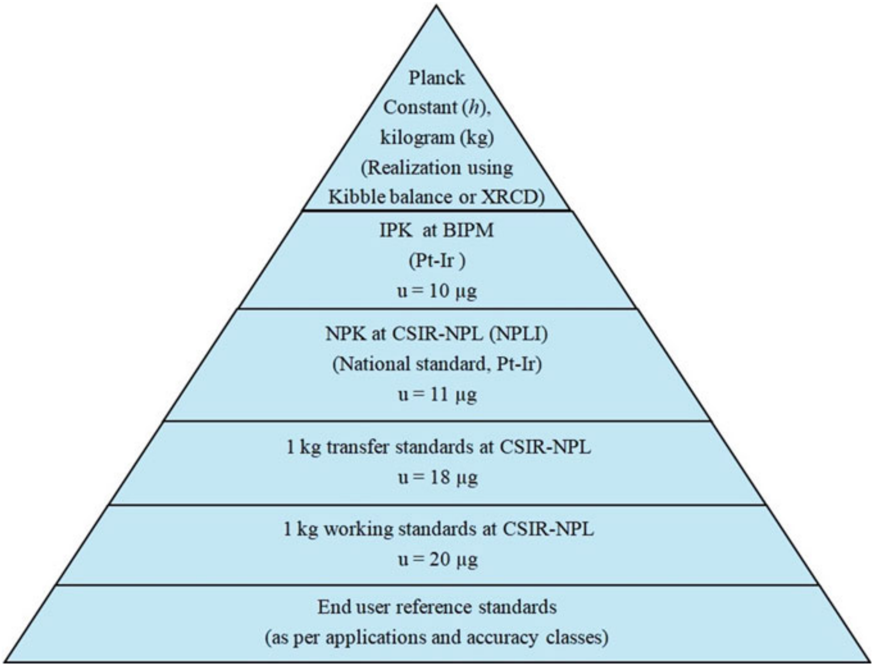


Fig. 2.10 The traceability chart for the mass realization after the implementation of redefined kilogram [26, 27]

of the values of *e* and *h*. Therefore, metrologists working at the highest precision level may need to do these slight adjustments of their standards and corresponding measurement uncertainty budgets.

- Any step changes in electrical units will be hidden by the drift or instabilities of the widely used secondary standards.
- The revised definition based on *e* has a consequence of the conversion factor between SI and electrostatic cgs system, e.g. fine structure constant.

The Kelvin Defined in Terms of Boltzmann Constant (*k*)

- The **kelvin** has been redefined based on Boltzmann constant, which relate the thermodynamic temperature to the energy, the coherent unit Jule. The material-dependent definition based on water triple point (TPW) has been abrogated, which has isotopic composition dependency in water samples.
- The value of the Boltzmann constant has been fixed with relative standard uncertainty of 3.7×10^{-7}. The primary thermometry methods such as *acoustic gas thermometry (AGT), dielectric constant gas thermometry (DCGT), Johnson noise*

thermometry (JNT), Doppler broadening thermometry and radiometric thermometry methods are successfully used and suggested in MeP-K for the realization and dissemination of redefined kelvin.

- Direct practical measurement of thermodynamic temperature is now possible at any point in the temperature scale. No primary method or the interpolation device is preferred in the direct realization.
- The thermodynamic temperature of TPW was exact to 273.16 K at the time of redefinition, However, after redefinition, its thermodynamic temperature T_{TPW} will have additional relative uncertainty of Boltzmann constant, about ±0.1 K [31]. TPW will remain as ITS-90 define fixed point without any additional realization uncertainty due to redefinition, to maintain the continuity of the previous measurements on T_{90}.
- Redefinition will have no instant effect on the ongoing measurement practices and the traceability of measurements, no noticeable effect for common users.
- It gives an opportunity for future improvements, and possible new temperature scale with defining fixed points closer to thermodynamic temperatures, after the assessments of T-T_{90} temperatures.
- The significant benefits have been seen in uncertainty levels of thermodynamic temperatures below 20 K and above 1300 K, and at extreme temperatures.
- The redefinition does not change the temperature value or realization uncertainties of the defined scales ITS-90 and PLTS-2000.

The traceability chart for the realization of Boltzmann constant based kelvin is given in Fig. 2.11.

The Mole Defined in Terms of Avogadro Constant (N_A)

- The **mole** has been redefined with respect to a specified number of entities (typically atoms or molecules) and no longer depends on the unit of mass, the kilogram.
- The value of Avogadro constant N_A adjusted by CODATA-2017 is $N_A = 6.022140758 \times 10^{23}$ mol^{-1} with a relative uncertainty of 2.0×10^{-8}.
- Practical realization of the definition of the mole with the smallest uncertainty was achieved in an International Avogadro Coordination experiment involving the determination of the number of ^{28}Si atoms (N) in a single crystal of Si. Both the constant N_A and h are realized by this method.
- Traceability to the mole can be established with all previously applicable methods with tables of atomic weights and the molar mass constant (Mu).
- Atomic weights are unaffected by the redefinition and Mu will remain 1 g/mol. The uncertainty is so small that the revised definition of the mole does not require any change to the common practice.
- The realization of mole in chemical entities is carried out using various primary methods. This includes gravimetric, use of the ideal gas law and electrolysis,

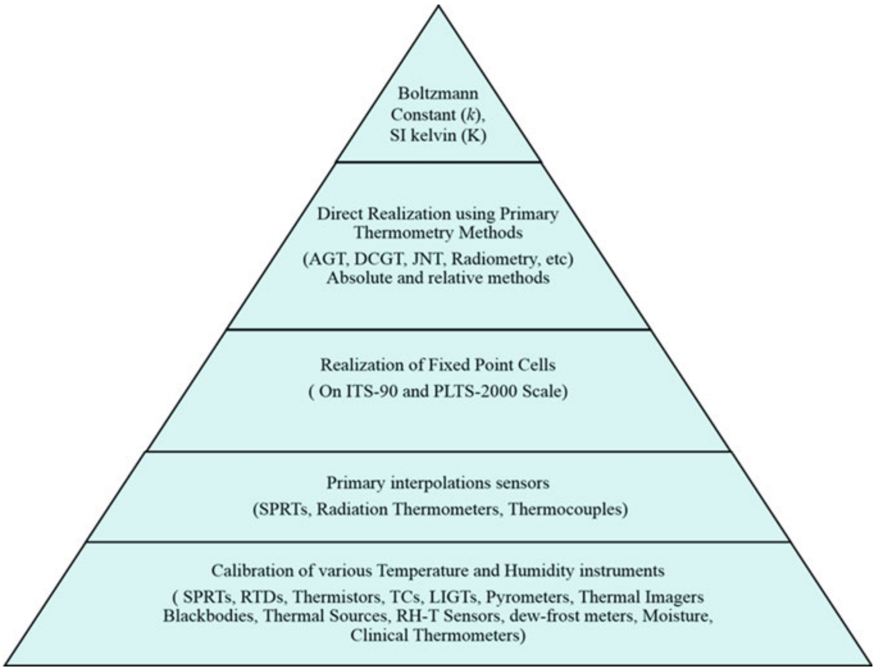


Fig. 2.11 The traceability chain of the realization of Boltzmann constant-based new kelvin

for the measurement of amount of substance concentration (mol/m^3), substance content (mol/kg) and substance fraction (mol/mol).

- The new definition eliminates any linkages between mass and amount of substance,
- The major implication of redefinition is that the mole is being used in the evolving areas of ultra-low chemical and biological quantities.
- It is stated here that there will not be any impact on the second, the metre and the candela because of the redefinitions of the kilogram, ampere, kelvin and mole.

The Implications on Second, Metre and Candela

- The definition of **second** continues to be in terms of the hyperfine transition frequency of the caesium 133 atom. The rewording has no effect on the traceability chain of second. In general, the time and frequency metrology is not impacted by any other redefinitions, instead major of the other units are linked with the second. Research on development on optical clocks is rigorously going on in the leading NMIs.
- The definition of **metre** remains in terms of the speed of light, one of the fundamental constants of physics. The MeP prepared for the implementation of new SI gave (i) direct measurement of light travelling time (time of flight) or (ii) indirect

measurement of light travelling time (optical interferometer) as the primary standard methods. Also the traceability support is required for the emerging areas of dimensional nanometrology, where the secondary method of realization of metre are used. Dimensional metrology practice does not need to be modified in any way and will benefit from the improved long-term stability of the system.

- The definition of **candela** remains in term of luminous efficacy of radiation at a specified frequency, and K_{cd}, is still linked to watt as being a technical constant for photometry. Traceability to the candela is established with the same measurement uncertainty via radiometric methods using absolute measurements by detectors. Since the value of h is fixed in mass redefinition, it will have certain effect on candela. The uncertainty associated with realization of candela is about 10^{-4} [32], order of magnitude higher than the expected changes due to redefinition of kilogram. Therefore, there is negligibly small implications due to the redefinition, on its dissemination and existing traceability services.

2.3.6 Derived and Other Non-metric Units

There are seven base units in the present SI. The units derived from these seven SI base units are called derived units, as specified by the SI. The base units are either dimensionless or can be expressed as a product of one or more of the base units, possibly also scaled by an appropriate power of exponentiation. Since the seven base units are redefined based on fundamental constants of nature, by fixing their numerical values, after the rigorous research work in last two decades, it is expected that there would be implications on some of the derived units. Therefore, CIPM advised SI to come up with the updated SI and the 9th edition is published in 2019 [9]. In this section, the descriptions on derived units, decimal multiplexes and sub-multiples and non-SI units are presented.

2.3.6.1 Derived Units

The implications of revised SI base units will be reflected in the derived units based on them. The units of the seven fundamental constants include both base and derived units. As the unit of mass, kilogram is redefined in terms of h, the realization uncertainty added to IPK or the NPK, about 11 μg is so small that the corresponding derived quantities of mass, such as density (kg m^{-3}), force (kg m s^{-2} which is 1 N or 1 N), pressure (kg m^{-1} s^{-2}, which is 1 Pa), will have noticeable change in their realization process or CMCs. Some of these derived units, such as pascal, are being realized using the similar primary method used to realize the fundamental constants. Any possible changes in the realization uncertainties of derived units would be evolved over the time. Derived units are the products of powers of the base units. The coherent derived units are the ones, where the numerical factor of this product is one, such as radian for plane angle. Some of the coherent derived units in SI system have special names given to them, such as Newton, pascal, farad. The list of 22 SI units with special names is given in Table 2.4. Seven defining constants can directly construct the set of seven base units and 22 SI units with special names. These 29 units are used in combination to make other SI units.

The series of prefixes in the form of decimal multiples and sub-multiples suitable for expressing the coherent SI units has been approved by the CGPM, to express larger or smaller quantities. However, when prefixes are used with SI units, it is not coherent. Prefixes can be applied to all 29 SI units of special names, except the base unit kilogram.

Table 2.4 The 22 SI units with special names and symbols [9]

Derived quantity	Special name of unit	Unit expressed in terms of base units	Unit expressed in terms of other SI units
Plane angle	radian	rad = m/m	
Solid angle	steradian	sr = m^2/m^2	
Frequency	hertz	Hz = s^{-1}	
Force	newton	N = kg m s^{-2}	
Pressure, stress	pascal	Pa = kg m^{-1} s^{-2}	
Energy, work, amount of heat	joule	J = kg m^2 s^{-2}	N m
Power, radiant flux	watt	W = kg m^2 s^{-3}	J/s
Electric charge	coulomb	C = A s	
Electric potential difference	volt	V = kg m^2 s^{-3} A^{-1}	W/A
Capacitance	farad	F = kg^{-1} m^{-2} s^4 A^2	C/V
Electric resistance	ohm	Ω = kg m^2 s^{-3} A^{-2}	V/A
Electric conductance	siemens	S = kg^{-1} m^{-2} s^3 A^2	A/V
Magnetic flux	weber	Wb = kg m^2 s^{-2} A^{-1}	V s
Magnetic flux density	tesla	T = kg s^{-2} A^{-1}	Wb/m^2
Inductance	henry	H = kg m^2 s^{-2} A^{-2}	Wb/A
Celsius temperature	degree Celsius	°C = K	
Luminous flux	lumen	lm = cd sr	cd sr
Illuminance	lux	lx = cd sr m^{-2}	lm/m^2
Activity referred to a radionuclide	becquerel	Bq = s^{-1}	
Absorbed dose, kerma	grey	Gy = m^2 s^{-2}	J/kg
Dose equivalent	sievert	Sv = m^2 s^{-2}	J/kg
Catalytic activity	katal	kat = mol s^{-1}	

Table 2.5 Examples of coherent derived units in the SI expressed in terms of base units [9]

Derived quantity	Typical symbol of quantity	Derived unit expressed in terms of base units
Area	A	m^2
Volume	V	m^3
speed, velocity	V	$m\ s^{-1}$
Acceleration	A	$m\ s^{-2}$
Wavenumber	Σ	m^{-1}
density, mass density	ρ	$kg\ m^{-3}$
surface density	ρ_A	$kg\ m^{-2}$
specific volume	v	$m^3\ kg^{-1}$
current density	j	$A\ m^{-2}$
magnetic field strength	H	$A\ m^{-1}$
amount of substance concentration	c	$mol\ m^{-3}$
mass concentration	ρ, γ	$kg\ m^{-3}$
luminance	L_v	$cd\ m^{-2}$

As described, the units of other derived quantities can be expressed in combination of the set of the seven base units and 22 derived units. Being large in number, it is impractical to give here a complete list of derived quantities and units. Some of the quantities and their coherent derived units, given in terms of base units, are listed in Table 2.5.

In addition, Table 2.6 lists the coherent derived units such as dynamic viscosity, entropy, energy density whose names and symbols also include derived units.

Each physical quantity is represented by only one coherent SI unit, irrespective of different form or special names and symbol. However, several different quantities shares the same SI unit, such as quantity heat capacity or the quantity entropy, the SI unit remains J/K. It is also true for the base quantity electric current and the derived quantity magnetomotive force the SI unit is the ampere. Therefore, unit alone can not specify the physical quantity. The same fact applies to the measuring instruments, read-out unit and quantity needs to be indicated clearly.

The ionizing radiation is quantized in terms of the SI unit becquerel rather than the reciprocal second is used. For the quantities absorbed dose and dose equivalent, the SI units grey and sievert are used and not joule per kilogram. Some of the special names are specifically added to avoid misinterpretations and hence the dangers to human life and health, such as becquerel, sievert and grey to avoid the mistakes. Also, some terms should be carefully used, such as temperatures or temperature differences, temperature difference of 1 K is equal to 1 °C, absolute values of temperature not coherent.

Table 2.6 Examples of SI coherent derived units whose names and symbols include SI coherent derived units with special names and symbols [9]

Derived quantity	Name of coherent derived unit	Symbol	Derived unit expressed in terms of base units
Dynamic viscosity	pascal second	Pa s	kg m^{-1} s^{-1}
Moment of force	newton metre	N m	kg m^2 s^{-2}
Surface tension	newton per metre	N m^{-1}	kg s^{-2}
Angular velocity, angular frequency	radian per second	rad s^{-1}	s^{-1}
Angular acceleration	radian per second squared	rad/s^2	s^{-2}
Heat flux density, irradiance	watt per square metre	W/m^2	kg s^{-3}
Heat capacity, entropy	joule per kelvin	J K^{-1}	kg m^2 s^{-2} K^{-1}
Specific heat capacity,	joule per kilogram kelvin	J K^{-1} kg^{-1}	m^2 s^{-2} K^{-1}
Specific entropy, specific energy	joule per kilogram	J kg^{-1}	m^2 s^{-2}
Thermal conductivity	watt per metre kelvin	W m^{-1} K^{-1}	kg m s^{-3} K^{-1}
Energy density	joule per cubic metre	J m^{-3}	kg m^{-1} s^{-2}
Electric field strength	volt per metre	V m^{-1}	kg m s^{-3} A^{-1}
Electric charge density	coulomb per cubic metre	C m^{-3}	A s m^{-3}
Surface charge density	coulomb per square metre	C m^{-2}	A s m^{-2}
Electric flux density, electric displacement	coulomb per square metre	C m^{-2}	A s m^{-2}
Permittivity	farad per metre	F m^{-1}	kg^{-1} m^{-3} s^4 A^2
Permeability	henry per metre	H m^{-1}	kg m s^{-2} A^{-2}
Molar energy	joule per mole	J mol^{-1}	kg m^2 s^{-2} mol^{-1}
Molar entropy, molar heat capacity	joule per mole kelvin	J K^{-1} mol^{-1}	kg m^2 s^{-2} mol^{-1} K^{-1}
Exposure (x- and γ-rays)	coulomb per kilogram	C kg^{-1}	A s kg^{-1}
Absorbed dose rate	grey per second	Gy s^{-1}	m^2 s^{-3}
Radiant intensity	watt per steradian	W sr^{-1}	kg m^2 s^{-3}
Radiance	watt per square metre steradian	W sr^{-1} m^{-2}	kg s^{-3}
Catalytic activity concentration	katal per cubic metre	kat m^{-3}	mol s^{-1} m^{-3}

Table 2.7 SI prefixes [9]

Factor	Name	Symbol	Factor	Name	Symbol
10^1	deca	da	10^{-1}	deci	D
10^2	hecto	h	10^{-2}	centi	C
10^3	kilo	k	10^{-3}	milli	M
10^6	mega	M	10^{-6}	micro	μ
10^9	giga	G	10^{-9}	nano	N
10^{12}	tera	T	10^{-12}	pico	P
10^{15}	peta	P	10^{-15}	femto	F
10^{18}	exa	E	10^{-18}	atto	A
10^{21}	zetta	Z	10^{-21}	zepto	Z
10^{24}	yotta	Y	10^{-24}	yocto	Y

2.3.6.2 Decimal Multiples and Sub-multiples of SI Units

The decimal multiples and sub-multiples make the representation of larges and smaller quantities easy, ranging from 10^{24} to 10^{-24} provided for use with the SI units and are presented in Table 2.7.

2.3.6.3 Non-SI Units that Are Accepted for Use with the SI

In the measurement systems, there are few non-SI units extensively used in daily practice, accepted by CIPM to use along with the SI. These non-SI units are listed in Table 2.8. However, whenever these units are used, some advantages of the SI are lost. The SI prefixes cannot be used with the non-SI units of time.

2.4 Conclusions and Future Perspectives

The existing SI system of units is the official system, adopted and accepted by most of the nations. It is a universal coherent system of seven base units and several other derived and conventionally accepted units. Recently, the metrology has undergone a sea change when in November 2018, world metrology leaders of 60 countries, all together voted for the adoption of redefined SI units system based on *fundamental constants of nature (FCN)*, which later on has been implemented all around world from 20 May 2019, the *World Metrology Day.* This has replaced the earlier system, which was mix of relation of some of the units with FCN and other based on artefact. As a matter of fundamentally importance, such novel innovations for next generation, useful for stakeholders, has been discussed in this chapter in a concise and articulate manner with full of resource data and pictorial depictions to clear concepts.

Table 2.8 Non-SI units accepted for use with the SI Units [9]

Quantity	Name of unit	Symbol for unit value in SI units	Quantity
Time	Minute	min	1 min = 60 s
	Hour	h	1 h = 60 min = 3600 s
	Day	d	1 d = 24 h = 86,400 s
Length	Astronomical unit	au	1 au = 149,597,870,700 m
Plane and	Degree	o	$1^{o} = (\pi/180)$ rad
Phase angle	Minute	′	$1' = (1/60)^{o} = (\pi/10{,}800)$ rad
	Second	″	$1'' = (1/60)' = (\pi/648{,}000)$ rad
Area	Hectare	ha	1 ha = 1 hm^2 = 10^4 m^2
Volume	Litre	l, L	1 l = 1 L = 1 dm^3 = 10^3 cm^3 = 10^{-3} m^3
Mass	Tonne	t	1 t = 10^3 kg
	Dalton	Da	1 Da = 1.660 539 066 60 (50) × 10^{-27} kg
Energy	Electronvolt	eV	1 eV = 1.602 176 634 × 10^{-19} J
Logarithmic	Neper	Np	
Ratio quantities	Bel Decibel	B dB	

The authors have tried to emphasize on importance of metrology and quality infrastructure required for a country. It is very important to know the right quantity with sufficient accuracy (uncertainty) to take the right decision in respective areas of applications like health, education, safety, economy, trade, etc. Metrology covers a vast area, since, all of us are surrounded by metrological applications in one way or other. Metrology has been existing since human civilization. Initially, though there was bit uniform measurement system applicable within small community only, but not at a large scale or community. In some of the cases, the measurement system was not even consistent and uniform within the country. This restricted the individual country to become self-reliant and fulfil all the needs of the citizen, because import–export as an essential part of the trade becomes difficult for them due to inconsistent measurement system. Hence, uniform measurement system is also essentially required for barrier free trade. Both CIPM MRA and ILAC MRA have fulfilled the requirements of WTO for barrier free trade between member nations. All the elements related to consistent and uniform measurement system are described.

As per applications, metrological activities are classified into scientific or fundamental metrology, industrial or applied metrology and legal metrology, but all are interrelated and their domains are well defined and discussed. For improving quality of products and human lives, the four pillars for establishing quality infrastructure, i.e.

custodian of national standards (NMI), documentary standards body, legal metrology department and accreditation body are described in details in chap. 3. India though has developed a good quality infrastructure for implementation of measurement system wherein four pillars, i.e. CSIR-NPL, BIS, LMD and NABL work as NMI, documentary standards body, legal metrology department and national accreditation body, respectively. All these organizations represent respective international metrological organizations, i.e. BIPM, ISO & IEC, OIML and ILAC, respectively, and doing their best for harmonization of measurement system and global acceptance of Indian products.

While going through the contents of the Chap. 1, the readers can easily understand the close relationship and interactions among government, academia, industry and civil society, through strong national quality infrastructure with metrology being an essential element. The SI system is a pivot around which modern metrology evolves. It signifies and disseminates the contemporary information about the SI system and its close relationship with measurement techniques, standards, measurement methods, industrial and technological developments. Special features discussed are the quality, metrology concept, its constituents, national and international measurement systems responsible for global compatibility, harmonization and acceptability of measurement standards, results and certification systems to remove trade barriers and improve the quality of life, environment and health. Such advanced information and sophisticated knowledge in the areas of high precision metrology, related research, innovation and resultant developments, specially manufacturing, health and environment exhibit close interaction to the modern methods of quality products, processes and services.

CSIR-NPL maintains ‘national standards’ of all the parameters except ionizing radiation. As per requirements of CIPM MRA, it maintains quality system based on ISO/IEC 17025 and ISO 17034 and periodically participates in international intercomparisons to maintain degree of equivalence in measurement system. At present, CSIR-NPL has registered total 236 CMCs (235 in physico-mechanical, electrical and electronic parameters and one in chemical parameter) which are available in ‘CMCs’ of BIPM KCDB. CSIR-NPL is moving forward to increase the capabilities in terms of addition of new parameters, enhancement of range, improvement of uncertainty, etc. to support industrial growth in the country.

CSIR-NPL not only maintains the national measurement standards but also disseminate the same to the various users, accredited laboratories, industries, etc. As a core pillar of NQI, it also supports the other three main pillars, i.e. NABL, LMD and BIS those in various capacities. Details of dissemination of measurement system are described in Chap. 3.

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