Chapter 1
Introduction: Metrology for All People for All Time

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Abstract In this introductory chapter, a brief account of international metrology program for ensuring a single, coherent system of measurements traceable to SI units throughout the world is presented. The making of National Physical Laboratory (CSIR-NPL) as the National Metrology Institute of India is highlighted. Various policy-making innovation models for the creation of knowledge economy and knowledge society are reviewed. A new and innovative model, i.e., Aswal model for inclusive growth is introduced. In this model, metrology fortifies strong interactions among the four helices of Quadruple Helix (QH) model, i.e., government, academia, industry, and society, to ensure the inclusive and sustainable growth of a nation. The implications of this model on various sectors contributing to national economy and quality of life are discussed, which include equality and trust in society, affordable health, high-quality science and technology, sustainable energy, clean environment, and climate change, international trade, cyber-physical systems, cybersecurity, etc. Finally, the roles of CSIR-NPL in nation-building are highlighted.

Measurement is the first step that leads to control and eventually to improvement. If you can’t measure something, you can’t understand it. If you can’t understand it, you can’t control it. If you can’t control it, you can’t improve it.
– H. James Harrington

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1.1 From a Landmark Initiative “Metre Convention” to a Milestone Decision “Revision of SI Units”

For all people for all time was the motive of a landmark initiative Metre Convention (Convention du Mètre), an international diplomatic treaty, for establishing a rational and universal set of measurement units, which was signed in Paris on May 20, 1875, by seventeen nations [1]. The Metre Convention led the worldwide focus on Metrology—the science of measurement—that resulted in an international structure, as depicted in Fig. 1.1, to ensure that all member states have identical capabilities on measurements [2]. This treaty founded the International Bureau of Weights and Measures (Bureau International des Poids et Mesures, BIPM) at Pavillon de Breteuil in Sèvres, France. BIPM is an intergovernmental organization under the authority of the General Conference on Weights and Measures (Conférence Générale des Poids et Mesures, CGPM) and under the supervision of the International Committee for Weights and Measures (Comité international des Poids et Mesures, CIPM). At present, CGPM has 62 Member States and observers from 40 Associate states and economies. The Republic of India signed the diplomatic treaty and became the Member State of CGPM in 1957 with CSIR-National Physical Laboratory (CSIR-NPL), New Delhi as its National Metrology Institute (NMI). CGPM meets once in every four years and has the responsibility to oversee the systems of measurement and adopt new definitions based on the recommendations of CIPM, which is supported by ten consultative committees related to Acoustics, Ultrasound, and Vibration; Electricity and Magnetism; Length; Mass and Related Quantities; Photometry and Radiometry; Amount of Substance; Metrology in Chemistry and Biology; Ionizing Radiation; Thermometry, Time and Frequency’ and Units. BIPM coordinates international metrology and the development of the measurement system in association with the NMIs of the Member States and the Associates States. The

Fig. 1.1 International agreement on metrology for ensuring a single, coherent system of measurements traceable to SI units throughout the world
directors of NMIs meet annually at BIPM, France, to discuss the scientific and technical aspects of the International System of Units (the SI units) and their applications. BIPM, therefore, provides the basis for a single, coherent system of measurements traceable to SI units throughout the world.

On 16 November 2018, during the 26th CGPM meeting held at Versailles, France, 60 member states voted for a landmark revision of the SI units on the basis of fundamental constants that describe the natural world [3]. These seven SI units are: (i) second (s): caesium hyperfine frequency ($\Delta \nu_{\text{Cs}}$), (ii) meter (m): the speed of light in vacuum (c), (iii) kilogram (kg): the Planck constant ($h$), (iv) Ampere (A): the elementary charge (e), (v) Temperature (T): the Boltzmann constant (k), (vi) mole (M): the Avogadro constant ($N_A$), and (vii) candela (cd): the luminous efficacy of a defined visible radiation ($K_{\text{cd}}$). On behalf of India, a team lead by Dr. D.K. Aswal, Director CSIR-NPL, voted for the revision of the SI units (see Fig. 1.2a). The values of these fundamental constants have been fixed without any uncertainty, and therefore, the SI units are the apex measurement standards across the globe for any kind of measurements. To highlight the significance of this revision, a wall of SI units was constructed at CSIR-NPL campus, as shown in Fig. 1.2b, in which the left and right wings of the butterflies show a correlation between the SI unit and the associated fundamental constant. On May 20, 2019, CSIR-NPL implemented the revised SI units in India. The detailed explanation of revised SI units, the calibration and measurement capabilities (CMCs), and the role of regional metrology organization, e.g., Asia Pacific Metrology Program (APMP) are presented in Chap. 2.

1.2 National Physical Laboratory—The NMI of India

1.2.1 A Brief Historical Account

On September 26, 1942, the Council of Scientific and Industrial Research (CSIR), India was established under the leadership of Sir Shanti Swarup Bhatnagar. In 1943 the governing body of CSIR decided to establish five national laboratories—National Physical Laboratory, National Chemical Laboratory, National Metallurgical Laboratory, Fuel Research Station, and Glass and Ceramics Research Institute. The foundation for the National Physical Laboratory was laid on 4 January 1947, eight months before India became independent, by Pandit Jawaharlal Nehru, the first Prime Minister of India in the presence of Sir Charles Darwin, Director NPL, UK. The CSIR-NPL was expected to fill a wide gap in the scientific and industrial organizations of India. The account of the foundation of CSIR-NPL was published in *Nature, February 8, 1947* issue [4]. At that point of time, India neither had a well-equipped laboratory to take up the measurement standards work nor had the statutory acceptance from BIPM for the mass and length standards. In addition, the country also did not have the capability to disseminate the length and mass standards with scientific precession for the use of industry. Therefore, the core mandate assigned to
CSIR-NPL was to maintain the fundamental and derived standards and to undertake research for achieving a high degree of accuracy in the measurements through regular inter-comparisons with standard laboratories of the world.

The responsibility assigned to CSIR-NPL clearly indicated that it would in future represent India in the BIPM and act as NMI of the country, and therefore, CSIR-NPL
was made a lab of unique importance to the Nation. The CSIR-NPL was formally
opened by former Deputy Prime Minister Sardar Vallabhbhai Patel on 21 January
1950, and an account of this ceremony was published in *Nature March 24, 1951* issue
[5]. The inaugural ceremony of CSIR-NPL was attended by a galaxy of eminent
people from many countries and a photograph of this obtained from the album of
CSIR-NPL is reproduced in Fig. 1.3. The prominent dignitaries present during the
inauguration were Mr. C. Rajagopalachari, Pandit Jawaharlal Nehru, Dr. Shyama
Prasad Mookerjee (at that time Minister of Industries and President of CSIR), Sir
Shanti Swarup Bhatnagar (Director of CSIR), Dr. K. S. Krishnan (Director, NPL),
Dr. K. N. Mathur (Assistant Director, Planning, NPL), Dr. Homi Jahangir Bhabha
(Director, Tata Institute of Fundamental Research), Sir Robert Robinson (President
of Royal Society), Prof. P. V. Auger (Director, Natural Sciences, UNESCO), Prof. W.
D. Englehardt, Prof. D. E. H. Rydbeck (Chalmers Institute of Technology, Sweden),
Prof. J. D. Bernal and Dr. E. U. Condon (National Bureau of Standards, USA now
National Institute of Standards and Technology, NIST). It is apparent that the world
had very high expectations from the CSIR-NPL towards the growth of India.

CSIR-NPL is the founding member of Asia Pacific Metrology Programme
(APMP)—the associations of national metrology institutes in the Asia region—
which is one of the six Regional metrology organizations (RMOs) of the world.
RMOs function within the framework of CIPM Mutual Recognition Arrangement
(MRA). Other 5 RMOs are: Intra-Africa Metrology System (AFRIMETS), Euro-
Asian Cooperation of National Metrological Institutions (COOMET), European
Association of National Metrology Institutes (EURAMET), Gulf Association for
Metrology (GULFMET) and Inter-American Metrology System (SIM). The RMOs
play an important role in establishing mutual confidence in the validity of calibra-
tion and measurement certificates (CMCs) issued by NMIs by carrying out key and
supplementary comparisons and other related activities.

### 1.2.2 Weights and Measures Act of India

The “Standards of Weights and Measures Act” was enacted by the Government
of India for the first time in 1956 to ensure that each of its citizens has an access
to uniform standards of weights and measures that are traceable to the SI units.
As mentioned earlier, India became a Member State of CGPM and BIPM in 1957.
Depending upon the developments on SI units at CGPM, the Rules under the Weights
and Measures Act are revised from time to time [6]. The Legal Metrology (National
Standards) Rules, 2011 under Chapter III states: “The work relating to the realization,
establishment, custody, maintenance, determination, reproduction and updating of
national standards of weights and measures shall, on the commencement of these
rules, be the responsibility of the National Physical Laboratory.” Therefore, this is
the core mandate of CSIR-NPL.

The Legal Metrology under the Ministry of Consumer Affairs has established
5 Regional Reference Standard Laboratories (RRSLs) at Ahmedabad, Bangalore,
Fig. 1.3  A photograph of the opening ceremony of NPL-India on January 21, 1950 (obtained from the album of NPL). From left to right: Mr. G. M. Bhuta, Dr. K. N. Mathur, Prof. O. E. H. Rydebeck, Prof. H. J. Bhabha, Prof. P. Auger, Dr. E. U. Condon, Dr. S. P. Mookerjee, Pandit Jawahar Lal Nehru, Sri C. Rajgopalachari, Sardar Vallabhbhai Patel, Dr. S. S. Bhatnagar, Dr. K. S. Krishnan, Sir Robert Robinson, Lady Robinson, Prof. W. A. Englehardt, and Prof. J. D. Bernal
Bhubaneswar, Faridabad, and Guwahati. These RRSLs work as a central agency between CSIR-NPL, the NMI of the country, and the state government laboratories for ensuring the metrological traceability to the SI units. The responsibilities of RRSLs also include testing of models of weights and measures, verification of secondary standards of state government, calibration of sophisticated weighing and measuring instruments, consumer awareness program, etc. In order to disseminate the mass and length standards to the actual users, the secondary and working standards are fabricated by the India Government Mint, Mumbai. Legal Metrology has the mandate to establish and enforce standards of weights and measures, regulate trade and commerce in weights, measures, and other goods which are sold or distributed by weights, measures or numbers.

1.3 Knowledge Creation Models for Inclusive Growth

Inclusive growth as defined by Organization for Economic Co-operation and Development (OECD) is the economic growth that is distributed fairly across society and creates opportunities for all [7]. The inclusive growth denotes that every member of the society should have a chance to participate in the development and get benefited from its economic outcome. The implementation of conditions required for inclusive growth must ensure the compliance of 3 dimensions of sustainability, i.e., economic, environmental, and social. In 2015, the United Nation along with its 195 member states agreed upon a global movement on the Sustainable Development Goals (SDG), as depicted in Fig. 1.4, which will improve the quality of lives of the people [8]. These goals need to be accomplished by the year 2030 through the involvement of government, business, media, academia, science and technology institutions, and civil society.

Fig. 1.4 The sustainable development goals (SDGs) of the United Nation to be implemented by the year 2030 for the improved lives of the people across the globe
Unfortunately, in December 2019 a new coronavirus (nCov19) pandemic has spread globally, which so far has infected millions of people and killed more than five hundred thousand. The positive side is that majority of the people are getting recovered [9]. The nCov19 induced disease, known as COVID-19, mainly gets transmitted through droplets released by an infected person during his exhales, coughs, or sneezes. In the absence of vaccines and medicines, the only way to control the spread of pandemic is to minimize person-to-person contacts. Therefore, most governments imposed upon nation-wide lock-down for months together, e.g., India imposed the lock-down during March-May, 2020. However, these lock-downs halted economic activities worldwide. Consequently, many people lost employment, which also incited them to return to their native places [10]. Therefore, governments are thinking a fresh to revive the economy for achieving set targets and accomplishments of SDGs.

In June 2020, the Government of India launched AtmaNirbhar Bharat (self-reliant India) mission to enable the resurgence in the Indian economy [11]. AtmaNirbhar Bharat focuses on the following five pillars: economy, infrastructure, system, vibrant demography, and demand. AtmaNirbhar Bharat envisions the upliftment of (i) businesses including micro, small and medium enterprises (MSMEs)—the backbone of manufacturing and services in India, (ii) poor people, including migrants and farmers, (iii) agriculture—enhanced production, (iv) new horizons of growth, including Industry 4.0, and (v) government reforms and enablers. AtmaNirbhar Bharat program in a way promotes the glocalization model, i.e., a concept that combines “globalization” and “localization”. The significance of the glocalization lies in the development of products that not only caters to the needs of high-end consumers and foreign markets but also are suitable for consumer segments of low-end and middle economy class [12]. Glocalization can only be empowered by the ‘knowledge economy’—a concept that was coined during the 1960s, which epitomizes production of new knowledge and their utilization for economic growth [13, 14]. Knowledge economy is a shift from earlier growth models, which depended upon the labor force and utilization of natural resources. Therefore, in order to make glocalization a successful model for inclusive growth, there is a need to envisage and develop policies that enable creation of new and usable knowledge. Several models of knowledge creation activities exist in the literature, which is summarized in Fig. 1.5. A brief overview of these models is described below.

### 1.3.1 Mode 1, Mode 2, and Mode 3 Models

One of the earliest knowledge creation models is known as Mode 1, which was conceptualized by Gibbons et al. [15]. In this model, the university research is only to gain fundamental knowledge and may not contribute to the industry or economy. The validation of knowledge is mainly done through peer-reviewed research publications. In Mode 2, the research is focused, interdisciplinary, and context-driven to enable knowledge for application, quality assurance, and economic and social accountability.
1.3.2 Triple Helix Model

The Triple Helix (TH) model of Etzkowitz and Leydesdorff is based on the university-industry-government interactions for innovation and economic development [17–19]. In this model, each sector namely university, industry, and government is represented by helices. The trilateral interactions amongst these helices are very complex in nature and the mutual bilateral interactions play important roles. In TH innovation model, universities produce knowledge through basic and applied sciences, industries produce products based on the knowledge and innovations, and the government makes regulations for marketing. In addition, the government plays a crucial role in
formulating appropriate policies and funding to support academia as well as industries. Industries may support academia through appropriate funding for further innovation. In addition, prolonged interactions can facilitate helices to change their partial characteristics by adopting the characteristics of others, which in turn, may lead to the creation of new hybrid institutions, e.g., technology transfer mechanisms, setting of science parks, incubation centers, hybrid organizations, etc. The TH model also helps in the advancement of individual helix, e.g., academia can find new context-driven research problems directly linked to the need of the industries; industries can utilize the skilled manpower obtained from universities to setup their own R&D centers; government as a policy may include curricula on industrial approach in the education system, which will enable to produce industry-oriented manpower for the national growth, etc.

1.3.3 Quadruple Helix and Quintuple Helix Models

Quadruple Helix (QH) model, proposed by Carayannis and Campbell, is an extension of Triple Helix model in which ‘civil society and media’ is added as the fourth helix [19, 20]. The inclusion of fourth helix is critical as the innovation approach becomes the user-driven and also tests the applicability of scientific knowledge for its robustness in the society. The QH model provides a broader picture of strong interactions amongst the helices that would assist in co-evolution, co-specialization, and co-development leading to innovations, e.g., technology, social reforms, products, services, etc. The QH model deals with the dynamics and evolution of these four helices and their impact on the economy and economic growth, unemployment, healthcare needs, environment, regulatory systems, and quality of life. The interactions amongst government-academia-industries-society though very complex in nature but need to be enhanced for the inclusive growth of a country. The QH model encourages networking of democracy, glocalization, knowledge economy, and knowledge society. Adding “natural environment” as fifth helix becomes the Quintuple Helix model, and therefore, deals with socio-ecological prospects for the sustainable development of knowledge-based society and economy, which also addresses climate change [20–22].

1.3.4 Aswal Model of Inclusive Growth

Though TH and QH models have been widely used in policy-making by developed nations, their utilities in developing nations are limited as they have the following major drawbacks.

(i) These models do not adequately elaborate essential infrastructure needed for their implementation, e.g., sophisticated equipment for conducting fundamental
studies, the manufacturing and quality-assurance facilities with industries, access to information and communication technologies (ICT) for fast access to information, skilled human resources, etc. These models probably assume that such basic requirements are available naturally, which of course is true for the developed world and India. However, implementation of these models in lesser developing nations can fail if prior critical analyses of the essential requirements are not done.

(ii) The co-evolution, co-specialization, and co-development amongst the helices for creation of knowledge-intensive activities are assumed to occur naturally. The models do not divulge essential underlying scientific/technological mechanisms required for the facilitation of strong interactions amongst the helices. Therefore, utilizing these innovation models in policymaking without any understanding interaction mechanisms may not yield fruitful and desired outcomes.

To address the issues raised above amicably, recently Aswal has analyzed the QH model, particularly to understand the interaction mechanisms amongst the helices, and proposed that metrology is at core of such interactions [23]. The Aswal model of inclusive growth, as shown in Fig. 1.6, illustrates broad roles and responsibilities of four helices namely, government, academia, industries, and society as well as their bindings through national quality-infrastructure (QI). A formal definition of the QI,

![Fig. 1.6 The Aswal model of inclusive growth [23]. The trustworthy data measured with SI traceability from the national quality-infrastructure facilitates strong interactions amongst government, academia, industry, and society, which is essential for the national economy and quality of life](image-url)
a brief overview of four helices is described later. A robust QI of a country ensures that all experimentally measured data are metrologically traceable to SI units, and therefore, have international equivalence. Such trustworthy measurement data are essential for the growth of individual helices as well as facilitating inherent trust for the collaboration amongst them in all directions, i.e., sideways, bottom-up, top-down, and crisscross, which in turn create knowledge and innovation for yielding high economy and improved quality of life. In addition, Aswal model envisages the requirement of qualified metrologists in each of the helices to ensure accuracies in the measurements along with associated uncertainties. The roles of government and society are paramount in sensitizing and formulation of industrial and science & technology policies that ensure sustainability through circular economy (a technology-enabled closed-loop system in which the creation of waste and pollution is minimized by recycling/reuse) as well as environmental issues and climate change.

A formal definition of QI has been proposed by the United Nations Industrial Development Organization (UNIDO), which states [24]: “The system comprising the organizations (public and private) together with the policies, relevant legal and regulatory framework, and practices needed to support and enhance the quality, safety and environmental soundness of goods, services and processes. The quality infrastructure is required for the effective operation of domestic markets, and its international recognition is important to enable access to foreign markets. It is a critical element in promoting and sustaining economic development, as well as environmental and social wellbeing. It relies on metrology, standardization, accreditation, conformity assessment, and market surveillance.”

In a country, the national quality policy ensures that institutions of the quality infrastructure, i.e., metrology, accreditation, and standards are well established. These QI institutions ensure the conformity assessment through calibration, testing, certification, and inspection. The QI institutions in developed nations, e.g., USA, are very strong, and therefore, have robust S&T and industrial policies, making them the highest gross domestic product (GDP) value nation in the world [25]. UNIDO supports the developing nations for their industrial growth and advocates for setting up a strong QI for the conformity assessment [26, 27]. If a nation does not have robust QI that ensures metrological traceability to SI units, a mistrust amongst government, academia, industries, and society may occur, which is illustrated here by citing a simple example. In a metro city, if the society feels that the pollution level is consistently high and posing risk to the health of its citizens and suppose the government data suggest that pollution is under control. To address this conflict, civil society may approach a court of law, which may order concerned regulator/government departments to provide reliable air-quality data and emission data from polluting sources (e.g., industries, vehicles, etc.). In order to obtain trustworthy data, the concerned regulator/government department will ensure that all used monitoring equipment is calibrated correctly. Therefore, equipment manufactures would be asked to provide certification of calibration from an accredited calibration laboratory. If the calibration laboratory finds that the equipment is not designed to measure the values correctly, the manufacturer (industry) may approach academia or scientific organization to help them to improve their designs. To verify the performance of design, the academia
of course must have an access to a calibration laboratory. If measurements of all
the concerned laboratories are not metrologically traceable to SI units, their results
may vary significantly owing to biases and uncertainties in the measurements, as
discussed in the next section. Thus, the absence of metrologically traceable QI in a
country, varying and unreliable data not only creates mistrust amongst stakeholders
but also creates a negative impact on the economy and quality of life. On the other
hand, if a country has a strong QI, the question of suspicion does not arise as all the
helices utilize accurate and precise measurement data traceable to SI units.

An internationally recognized QI in a country facilitates the growth of individual
helices in the Aswal model. Government and regulators are benefited from having
trustworthy data inputs for the formulation of national policies related to science and
technology, industrial development, international trade, etc. as well as their imple-
mentations. The academia and S&T organizations have the advantages of getting
appropriately calibrated equipment, which enables them to get high-quality scien-
tific data for research as unwanted data can easily be disregarded. The original data
contribute to discovering new fundamental phenomena in sciences as well as innova-
tive technologies. The accurate and precise measurements allow industries to produce
internationally competitive products according to trade standards. QI also satisfies
the consumers as they can trust the quality of products and services manufactured
and/or imported in the country.

1.3.4.1 The Four Helices of India

The four helices of India namely government, academia, industry, and society are so
massive that it is next to impossible to provide a detailed description of them, and
therefore, only a brief sketch is presented here.

Government

The Government of India is constitutionally a democratic republic and has a union
government of 28 states and 8 union territories. The union has the legislative, exec-
utive, and judicial authority. The government creates steering mechanisms though
the formation of the policies and regulations as well as financing for the country’s
growth in the right direction. The present Government has launched several new
schemes for the development of the country and to enhance the quality of life of
its citizens. Some of the schemes are Skill India Mission; Make in India; Digital
India Mission; Start-up India; Stand Up India; Pradhan Mantri Kisan Samman
Nidhi (PM-KISAN) Scheme; PM Garib Kalyan Yojana (PMGKY); Pradhan Mantri
Kisan Pension Yojana; Jal Shakti Yojana; Jan Dhan Yojana; Swachh Bharat Mission;
Sansad Adarsh Gram Yojana; Beti Bachao Beti Padhao; Hridaya Plan; PM Mudra
Yojana; Ujala Yojna; Prime Minister Jeevan Jyoti Bima Yojana; Atal Pension Yojana;
Pradhan Mantri Suraksha Bima Yojana; Gold Monetization Scheme; Setu Bhartam
Yojana; Atal Bhujal Yojana (ABY); National Mission for Clean Ganga (NMCG);
### Table 1.1  A partial list of regulatory bodies in India [23]

| Category                        | Authority                                                                 |
|---------------------------------|----------------------------------------------------------------------------|
| Agricultural and processed food products | Agricultural and Processed Food Products Export Development Authority (APEDA) |
| Digital signatures              | Controller of Certifying Authorities (CCA)                                |
| Drugs and medical devices       | Drugs Controller General of India (DGCI)                                  |
| Electronics and IT              | Standardization Testing and Quality Certification (STQC)                  |
| Energy efficiency               | Bureau of Energy Efficiency (BEE)                                         |
| Environmental pollution         | Central Pollution Control Board (CPCB)                                    |
| Export certification            | Export Inspection Council (EIC)                                           |
| Food safety                     | Food Safety and Standards Authority of India (FSSAI)                      |
| Forensic                        | Central Forensic Science Laboratory (CFSL)                                |
| Industrial policy               | Department of Industrial Policy and Promotion (DIPP)                      |
| Petroleum products              | Petroleum & Natural Gas Regulatory Board (PNGRB)                         |
| Radiation safety                | Atomic Energy Regulatory Board (AERB)                                    |
| Renewable energy                | Ministry of New and Renewable Energy (MNRE)                               |
| Securities market               | Securities and Exchange Board of India (SEBI)                             |
| Telcom regulatory               | Telcom Regulatory Authority of India (TRAI)                                |
| Weights and measures            | Legal Metrology                                                           |

Aarogya Setu; Ayushman Bharat; Unified Mobile Application for New-age Governance (UMANG); Pilgrimage Rejuvenation And Spirituality Augmentation Drive (PRASAD) Scheme, Prime Minister’s Citizen Assistance and Relief in Emergency Situation (PM CARES); etc. As mentioned earlier, to counter the economic slowdown due to COVID-19 pandemic, government of India has made path-breaking reforms and pumped in >265 billion US dollars as stimulus package, which is equivalent to ~10% of India’s GDP. Honorable Prime Minister gave a clarion call for AtmaNirbhar Bharat or Self-Reliant India Movement and outlined five pillars—economy, infrastructure, system, vibrant demography, and demand [28]. In order to implement these schemes, various government departments/regulators related to manufacturing, food, energy, health, environment, electronics, export, etc. are listed in Table 1.1, and all of them need national quality-infrastructure for conformity assessment.

The Academia—Universities, Science and Technology Institutions

The academia—universities and science and technology institutions, have the responsibility for the education, research and development, innovations, incubation, and
spin-offs. India has a strong network of universities and S&T institutions. University Grant Commission (UGC) has recognized 825 universities belonging to central, state, deemed, and private [29]. UGC has also established 15 professional councils. In addition, the country has many other central institutions including, Indian Institute of Sciences (IISc), Indian Institutes of Technology (IITs), National Institutes of Technology (NITs), Indian Institutes of Management (IIMs), Indian Institutes of Information Technology (IIITs), School of Planning and Architecture (SPAs), National Institute of Science Education and Research (NISER), Indian Institutes of Science Education and Research (IISERs), All India Institute of Medical Sciences (AIIMS), etc. India also has many specialized departments and organization for R&D, such as Department of Atomic Energy (DAE), Indian Space Research Organization (ISRO), Defense Research and Development Organization (DRDO), Indian Council of Medical Research (ICMR), Council of Scientific and Industrial Research (CSIR), Indian Council of Agriculture Research (ICAR), etc.

Industries

The industries manufacture the products and related services and are major contributors to the economic growth of a country. India has a strong industry base almost in all sectors [30] including agriculture; automobiles and auto components; aviation and aeronautics; banking, finance and insurance; cement and building materials; engineering and manufacturing’ gems and jewelry; healthcare; information technology; media and entertainment; metals, metallurgy and mining; oil and natural gas; pharmaceuticals; power, railways; renewable energy; steel; telecommunication; textiles; tourism and hospitality, etc.

The Civil Society and Media

The civil society and media facilitate the integration of local cultural values to the innovation and provide a platform to generate the reputation and acceptability of the products. India has a current population of 1.32 billion, which is likely to reach 1.54 billion by 2035 [31]. India with such a large population is also known to be a country of magnificent paradoxes, e.g., very poor and very rich people, extreme cold and extremely hot weather conditions, traditional knowledge and modern technologies, demographics and democracy, culture and modernity, etc. Therefore, civil society and media will have to play a dominant role in the realization of Aswal model for inclusive growth.

1.3.4.2 Quality-Infrastructure of India

Figure 1.7 summarizes India’s QI institutions namely, metrology, accreditation, and standards as well as their international affiliations. The scientific metrology is the
Fig. 1.7 The Quality infrastructure of India and its international recognition

responsibility of CSIR-NPL [32] along with the Bhabha Atomic Research Centre (BARC) [33], the designated institute for the ionization radiation. The legal and enforcement of metrology is the responsibility of Legal Metrology, Ministry of Consumer Affairs, Government of India. Various boards under the Quality Council of India (QCI) [34] namely NABCB, NABET, NBQP, NABH, and NABL look after the accreditation and certification. Indian Standards are developed by the Bureau of Indian Standards (BIS) [35]. Regardless of having international affiliations of QI institutions, the QI strength of countries can be widely different. The QI strength of a country depends upon (i) overall international capabilities of each QI institution and (ii) the coordination amongst the QI institutions within the country and their effective dissemination to various stakeholders across the country. As discussed in Aswal model, the responsibilities of QI institutions are predominantly high in realizing the national schemes of government for the economic growth and improvement of quality of life.

One of the major roles of QI is to ensure that the measurement results are accurate and precise. The reliability of test/experiment results is important for decision making in both scientific research and routine daily life with different professions. For example, doctors use the patient’s blood test values for the presence/absence of a particular disease, environmental engineers test samples of drinking water for the presence of toxic elements and harmful bacteria and determine whether their concentration is within the safety limits, import agencies may test the items for the harmful contaminates, various regulators as listed in Table 1.1 may seek tests results for the compliance of technical regulations, so on. As shown in Fig. 1.8, the measured
value from a test may deviate from the actual value due to various sources of errors. In addition, if the measuring equipment is not appropriately calibrated or the standard or control samples are not used during the measurements, the measured value may exhibit bias or drift/change with time. A bias and/or large uncertainty in the measurement values can lead to a big problem where test results are used as binary classification, i.e., either positive or negative. One can end up getting false positive, i.e., test result wrongly shows presence of a disease but in reality, it is not present, or false-negative, i.e., test result wrongly indicates absence of the disease but in reality, it is present. Both false negative and false-positive results are not only bad for patient but can also create problems in the society. For example, if the Covid-19 test is a false negative, the patient unknowingly will keep spreading the disease in society. On the other hand, if the Covid-19 test is false positive, the patient will have to undergo unnecessary trauma of quarantine and treatment. Therefore, all the experimentally measured values should be close to the true value with minimum uncertainty, and this can be ensured if the country has a strong QI.

Metrology in India

The responsibility of CSIR-NPL, in collaboration with NABL and BIS, is to ensure that all the testing labs across the country (which are estimated to be >400,000 in numbers) produce accurate and precise measurement values. A measurement is valid
Fig. 1.9 Two routes of establishing an unbroken chain of measurement traceability: (a) using the traceability pyramid. (The pyramid was installed at the NPL campus in 2016 for mass awareness based on the concepts of Dr. D. K. Aswal and Dr. V. N. Ojha). (b) using the certified reference material only if: (i) the measurement has demonstrated an unbroken chain of traceability to the SI unit though the primary/national measurements available at the NMI, and (ii) the measurement uncertainty has been estimated in each of the transfer chains. In the absence of either of the two, the measurement would be purely indicative with no legal validity, i.e., would not be accepted in case of any dispute. The measurement traceability, as shown in Fig. 1.9, can be obtained through two routes: (i) calibrating the measuring instrument through working standards, reference standard, secondary/primary standards to the SI units, as depicted in the photograph of a Traceability Pyramid installed at the NPL campus; and (ii) using the certified reference materials (CRM), which are trademarked as Bhartiya Nirdeshak Dravyas (BND®) by CSIR-NPL.

CSIR-NPL maintains a quality system in accordance with ISO 17025:2017 and ISO 17034, and has the following responsibilities:

(i) To actively participate in technical meetings of BIPM and APMP related to the development of metrology. RMOs like APMP, in association with BIPM, homogenize measurement capabilities across the world through NMIs.

(ii) Realization of primary/national measurement standards and establish the calibration and measurement capabilities (CMCs). The joint committee of the regional organizations and the BIPM (JCRB) analyses the CMCs of NMIs and the information is uploaded on the website of Key Comparison Database of BIPM (KCDB-BIPM) [36]. CSIR-NPL has 236 CMCs and 130 key/supplementary comparisons in metrology areas related to physicomechanical, electrical and electronics, time and frequency, chemistry, etc. In addition, BARC has 52 key/supplementary comparisons in the area of ionization radiation. A detailed account of these is presented in the subsequent Chapters.
However, as shown in Fig. 1.10, the CMCs of India are far low as compared to NMI s of developed nations viz. USA (1889), China (1554), Japan (1126), Germany (1563), UK (1136). Large number of CMCs indicate that country has measurement capabilities of international equivalence in several frontiers of science and technology. Thus, both CSIR-NPL and BARC have enough scope to enhance their CMCs at the KCDB.

(iii) Dissemination of measurement traceability to all the stakeholders in the country using calibration of measurement equipment and/or CRMs or BNDs. Over the past 7 decades, CSIR-NPL has carried out dissemination of primary/national measurement facilities to several thousands of industries and strategic sectors. CSIR-NPL worked as “Growth Engine” of the country as these calibration services facilitated Indian industries to enhance the quality of their products.

In 2016, based on the need of the country, CSIR-NPL reorganized itself to take up the metrology in areas of Indian Standard Time (IST), physico-mechanical, electrical and electronics, environment, energy, biomedical, quantum standards, materials, etc., as depicted in Fig. 1.11. Of course, the setting of new primary/national standards require high capital investment, trained manpower, and international inter-comparison. CSIR-NPL has taken up setting up of primary standards in the areas of air quality and emission monitoring, solar cell efficiency, biomedical devices, etc. CSIR-NPL produces the CRMs under the trademark of Bhartiya Nirdeshak Dravya (BND®) and has a national mechanism for the production of BNDs in collaboration with reference material producers in the country.

Legal metrology through appropriate law enforcement transfers the benefits of metrology to common citizens of the country by ensuring fair trade through correct measurements. Legal Metrology ensures this by Type approval of measuring equipment; calibration, verification, and market surveillance of measuring equipment; and
controls on pre-packaged goods. Legal metrology is an integral part of the technical regulation regime and complies with the requirements of the Agreement on Technical Barriers to Trade (TBT Agreement) of the World Trade Organization (WTO) [37]. Legal metrology also defines the roles and responsibilities of central and state governments in the implementation of the Weights and Measure Act of the government. The central government deals with matters related to the implementation of International Organization of Legal Metrology (OIML) recommendations [38], formulation of national policy and laws on weights and measures, technical regulations, training, and setting up of precision laboratory. State and union territory governments have the responsibility for the enforcement of the laws framed by the central government through their offices of the Controller of Legal Metrology (Weights and Measures). The nationwide network of the legal metrology laboratories is responsible for the calibration and testing of equipment of weights and measures, ensuring the measurement traceability is available to end-users. Legal metrology has initiated a nationwide program on dissemination of Indian Standard Time (IST) to common citizens.
Bureau of Indian Standards (BIS) is an exclusive standardization body of India for development of Indian Standards (IS). BIS is a member International Organization for Standardization (ISO) [39] and International Electrotechnical Commission (IEC) [40]. Standards offer numerous economic benefits to industries: (i) assist in the optimization of internal operations, which may lead to reduced time of operation, enhanced productivity, reduction procurement costs, and reduction in waste; (ii) support in the utilization of innovative processes for scalable manufacturing of new products; and (iii) facilitate in identifying new domestic and export markets. More than 20,000 Indian standards have been developed so far by 344 technical committees belonging to 16 Division Councils of BIS. Many technical committees act as mirror committees at ISO and IEC. Specialized Standards are also developed by many regulators, as listed in Table 1.1, and often these standards are adopted as IS by BIS. Indian standards are widely used for ensuring necessary characteristics of products and services, which include quality, reliability, safety, efficiency, environment-friendly, and interchangeability. BIS also has schemes of conformity assessment, e.g., ISI certification for products, hall-marking of gold jewelry, and foreign manufacturers’ certification scheme (FMCS), etc.

The most widely adopted ISO standards are: (i) quality management systems (ISO 9001), (ii) general requirements for the competence of testing and calibration laboratories (ISO/IEC 17025:2017), (iii) environmental management systems (ISO 14001), (iv) conformity assessment—general requirements for proficiency testing (ISO/IEC 17043:2010), (v) general requirements for the competence of reference material producers (ISO 17034:2016), (vi) information security management systems (ISO/IEC 27001:2005) and (vii) risk management (ISO 31000:2009).

NABL so far has granted >5600 accreditations to calibration laboratories, testing laboratories, medical laboratories, proficiency testing providers and reference material producers. The scope of NABL accreditation are:
(i) calibration laboratories: mechanical, thermal, electro-technical, optical, fluid flow, radiological and medical devices;

(ii) testing laboratories: chemical, electrical, electronics, biological, fluid flow, mechanical, non-destructive testing (NDT), photometry, radiological, forensic, diagnostic radiology QA testing and software and IT system;

(iii) medical laboratories: clinical biochemistry, hematology and immunohematology, clinical pathology, histopathology, microbiology, and infectious disease serology, genetics, cytopathology, flow cytometry, nuclear medicine (in vitro tests only). In the era of nCov19 pandemic, through on-line assessment procedure, NABL accredited >300 medical testing laboratories for RT-PCR RNA Virus/COVID-19, enhancing the capabilities of the country for timely testing of large number of patients;

(iv) reference material producers: physical properties, chemical composition, engineering properties, biological and clinical properties, and miscellaneous properties.

NABL accreditation has been mandated by the majority of regulators listed in Table 1.1 for ensuring conformity assessment of their schemes/regulation, and therefore, provides an advantage to industries in getting their products to get tested from NABL accredited laboratories. Similarly, reference materials producers have distinct advantages of getting accredited by NABL to ensures metrological traceability is from CSIR-NPL. In addition, they can produce and market their certified reference materials under the trademark of BND®️, which has visibility in the international market.

The number of testing/calibration laboratories in India is >40,000 and only 5600 laboratories have been accredited so far by NABL. Therefore, in order to provide accreditation to such a large number of laboratories while ensuring the metrological traceability to SI units, NABL needs to create two tiers of laboratories. Tier-1 calibration laboratories: these would be equivalent to those of regional reference laboratories of Legal Metrology and obtain measurement traceability directly from the CSIR-NPL. Therefore, these Tier-1 laboratories are expected to have much lower measurement uncertainty. Laboratories falling under government and/or private sectors having essential infrastructure can be assigned Tier-1 grade after the approval from CSIR-NPL. Tier 2 calibration laboratories: rest of the laboratories would be accredited under Tier-2 and they will obtain measurement traceability from Tier-1 laboratories. Tier-2 laboratories will disseminate measurement traceability to testing laboratories across the country.

The conformity assessment bodies (CABs) not requiring the metrology traceability are accredited by other boards of QCI, namely the National Accreditation Board for Certification Bodies (NABCB) [44], National Accreditation Board for Hospitals and Healthcare Providers (NABH) [45], and National Accreditation Board for Education and Training (NABET) [46]. The NABCB operates under the framework of ISO 17011 and accredits CABs for inspection bodies (e.g., BIS for product certification), medical devices, management systems for food safety, environmental monitoring, information security, health safety, occupational hazards, energy,
etc. NABET provides accreditation in the management of education and training and NABH in management of hospitals. Both NABET and NABH function under self-regulation.

1.4 Implications of Aswal Model

As discussed in the previous section, India has a robust and effective system of government, academia, industries, and civil society. In addition, the quality-infrastructure in India is reasonably well established. In order to ensure the *AtmaNirbhar Bharat* with a goal of $5 trillion economies by 2025 [47], implementation of Aswal model of inclusive growth would be highly beneficial. In this model, metrology is at the core of the national quality infrastructure, which is a must for all the helices for creating knowledge and innovation for the knowledge economy, sustainable development, and knowledge society. As depicted in Fig. 1.12, the Aswal model has an enormous impact, which is discussed below.

1.4.1 Technology Development and Industrialization

One of the effective methods to enhance the national economy and eliminate poverty is to undergo sustainable industrialization with a focus to cater needs of local market as well as for export. UNIDO measures the industrialization level of a country using an indicator known as manufacturing value added (MVA) per capita, which is a difference between the net manufacturing output and intermediate inputs. Figure 1.13 shows the MVA per capita of leading economies of the world for the years 2014-2019.
It is evident that India has to work very hard on industrialization to catch up the developed world.

In India, the Micro, Small and Medium Enterprises (MSMEs) play a significant role in economic growth by providing the solutions to the local needs, develop products and services at reasonable prices, provide large employment opportunities (second after the agriculture sector) to both rural and urban population, and act as nucleation for entrepreneurship and innovation. Under AtmaNirbhar Bharat program, the government has taken a pathbreaking step not only to incentivize MSMEs but also made fundamental changes the way MSMEs are classified, i.e., annual turnover up to 5 crores (Micro), 10 crores (small), and 250 crores (Medium) [49]. With these incentives, MSMEs are destined for spiral growth. However, on the technical front, MSMEs face a challenge of non-availability of appropriate technologies as the know-how of technologies obtained from academia and research institutions are often imperfect and difficult to reproduce for mass manufacturing. Here the applicability of Aswal model for development of quality products from a technology obtained from academia is highlighted.

The maturity level of technology at different stages is often assessed by Technology Readiness Levels (TRL) measurement system, initially developed by NASA for space technology and ranked from TRL-1 to TRL-9, which later on was adopted worldwide for other technologies [50]. Figure 1.14 depicts a typical progression from TRL-1 to TRL-9, roles of involved stakeholders along with that of national quality infrastructure. Broadly the evolution of TRLs can be classified into four parts, i.e., concept (TRL-1 and TRL-2), development (TRL-3 and TRL-4), manufacturing (TRL-5 and TRL-6), and trading (TRL-8 and TRL-9).
Fig. 1.14 A typical progression of technology from TRL-1 to TRL-9, concerned stakeholders, and their responsibilities. It is noted that a strong national metrology infrastructure is a must for all the TRLs.

Usually, the TRL-1 and TRL-2 are taken up by academia and evaluated for concepts based on scientific research that can be translated into product development. The experimental proof for the technology has also been established to a certain extent. TRL-1 and TRL-2 require laboratories with S&T facilities to have creditable metrology to ensure that experimental results are genuine enough for the analyses for ensuring that if concept can be taken further or not for the development.

TRL-3 and TRL-4 belong to the development stage of the product. TRL-3 is assigned when the design and development of the product begin and a proof-of-concept is established. TRL-4 is the stage when the creditable level of the prototype has been built. All of the components and tested and validated independently, which requires a strong quality infrastructure in the country. TRL-5 is the rigorous testing and validation of the prototypes developed at TRL-4 under the simulated environmental conditions equivalent to those where the product is eventually going to be deployed. The technology advances to TRL-6, once the conformity assessment of the product developed at TRL-5 is complete. At TRL-6 the product undergoes for manufacturing and undergoes process optimization and quality assurance, which also demand a strong quality infrastructure. TRL-7 is a further extension of TRL-6 and requires the testing of the product under the actual environmental conditions. TRL-8 and TRL-9 are making the product ready for the trading. At TRL-8, the standard and regulatory compliance of the technology are ensured. In order to issue a certificate of regulatory compliance of the product, the regulators, as discussed earlier, would require the quality infrastructure for obtaining trustworthy test results. In TRL-9 the societal and market needs are assessed and technology is launched in the market. It is
evident that a strong metrology infrastructure in the country is essential for pushing the technology from TRL-1 to TRL-9 with technologies suitable for zero defects manufacturing. The growth of MSME sector would depend on how effectively they are utilizing the national quality infrastructure of the country.

As discussed above, metrology is a key to industrial production. In the past metrology tools and methods were evolved along with the advancement of industrialization. Industry 1.0 utilized the mechanical instruments for products and processes, which was well supported by the physico-mechanical metrology. Industry 2.0 utilized electricity to facilitate mass production using advanced manufacturing processes and associated sophisticated measurement technologies. Industry 3.0 was marked by the automation of manufacturing. The concept of automated coordinate measuring machine (CMM) emerged that combines mechanics, electronics, sensors, and programmable logic. In Industry 4.0, the manufacturing industry will undergo digitization and virtualization [51] and this new concept of digital metrology is still evolving.

1.4.2 Cyber-Physical Systems and Cyber Security

The Industry 4.0 paradigm is based on the intuitive interactions between the machines and humans, which will be governed by the advancements in the cyber-physical systems (CPS). In CPS, through integrated physics and logic, deep intertwining amongst the analog, digital, physical, network, and human components are engineered to obtain desired functions, i.e., automated and self-organizing physical processes in real-time [51]. Therefore, new industries will have fully automatic (auto-configuring, auto-adjusting, and auto-optimizing) production environment, leading to greater quickness, flexibility, and cost-effectiveness. Therefore, these manufacturing plants would require highly skilled workers, who will have to work from the central control room and interacting directly with synchronized intelligent machines. The application of CPS includes autonomous automobiles, smart grid, manufacturing, robotics systems, smart cities, healthcare, aerospace, chemical processes, civil infrastructure, energy, entertainment, consumer appliances, emergency response, traffic flow management, indoor automatic agriculture, etc., which are going to improve the quality of life.

Metrology remains the backbone of the “autonomy” in the CPS technologies [52]. In CPS, the decision-making is to be carried out by the system itself based on the received measurement data. Therefore, in CPS, first task is to measure the “intelligence” of a system, and for this metrology plays a predominant role in identifying indicators of intelligence and their measurement. CPS requires a constant collection of measurement information using calibrated sensors and actuators. The real-time application of CPS can only be ensured if all of its components—physical and software, are synchronized to Universal Coordinated Time (UTC) through the official/legal time of the respective country, e.g., Indian Standard Time generated by
CSIR-NPL, and this is discussed in detail in Chaps. 4 and 5. Therefore, management of complex but critical time synchronization for achieving the real-time CPS is another key component of time and frequency metrology. Time metrology also ensures secure and trusted timestamping which once recorded cannot even be modified by its owner, and therefore, is essential for safe national digital services, e.g., electronic signatures, electronic seals, electronic delivery services, electronic time stamps, and website authentication [53]. Electronic timestamp provides the guarantee of accuracy of bound date and time to the data. The metrology of CPS is still evolving as is complex in nature due to various factors: (i) a large number of sensors are often used for measurements and most of them have different functional output; (ii) drift in the characteristics of sensors and other electronic components due to changes in environmental conditions; (iii) all components need to be synchronized in time for obtaining real-time processing of measurements; (iv) software of device components are usually different (different manufacturers use different data transfer protocols), which cause problems in data transfers without errors, etc. However, it is expected that in the very near future, metrology for Industry 4.0 would be ready.

1.4.3 Affordable Healthcare and Safety

A strong healthcare system is important keeping in view population growth as well as the aging population. Affordable healthcare requires accurate physical, chemical, and biological measurements in the everyday life of people as they are fundamental in the prevention, diagnosis, and treatment of disease [54]. Various aspects of a patient’s health can be diagnosed correctly if diagnostic medical equipment (e.g. clinical thermometer for body temperature; stethoscopes for the sounds originating from hearts, lungs, etc.; electrocardiographs for measuring the electrical activity of the heart; ophthalmoscopes to see into the fundus of a patient’s eye; medical X-rays; magnetic resonance imaging (MRI); computed tomography (CT) scan; and the list is very long) are calibrated to ensure the metrological traceability. Once a correct diagnosis is made, the doctor can easily recommend an appropriate treatment plan. Even during the treatment, the quality of medicine as well as safe and effective delivery of therapies need to be ensured. Therefore, there is a growing interest in ensuring the metrological traceability of the medical devices as well as in regulation on conformity assessment of medical devices for their measuring functions. The innovation in the diagnosis and treatment of diseases is essential for the good health of humans and enhancing their life expectancy. Metrology ensures accurate measurements to assess the performance of diagnostic methods and therapies, and ensure the effective treatment of patients. In order to understand therapy-induced changes and their subsequent control for treatment of a patient, accurate measurements on physiological variables are essential. Wrong measurements can endanger patient safety and put critically ill patients in deep troubles.

Use of appropriately calibrated medical devices will facilitate affordable healthcare owing to the following advantages: (i) the false positive or false negative results
are minimized; (ii) unnecessary harassment to the patient for repeated and unnec-

essary associated tests; (iii) right treatment and therefore less medicinal side effects
to the patient; and (iv) reduction in the treatment cost. This also reduces the burden
in government hospitals, where the healthcare facilities are limited. CSIR-NPL is
playing a key role in the calibration of biomedical equipment, which is elaborated in
Chap. 15.

1.4.4 Clean Environment and Climate Change

A delicate balance between the protection of the environment to keep the air clean
enough for breathing and sustainable industrial growth for the economy and job
creation with environmental legislation is a challenging task. This balance can be
achieved through the application of metrology. Measurements of ambient air quality
parameters (i.e., particulate matters, CO, CO₂, ozone, SO₂, etc.) and emission from
the industries with part per billion levels of accuracies are crucial for managing and
protecting the environment. A terrestrial network of pollution measuring equipment
is used for monitoring air quality, while climate change studies are often carried on
data collected from satellite-borne measuring devices. Analyses of such robust and
trustworthy environmental data obtained from metrologically traceable equipment
provide useful information about climate change or pollution emission trends, which
can be utilized for appropriate remedial actions. To ensure the generation of reliable
data, most nations enforce mandatory certification of pollution measuring equipment.
In India, CSIR-NPL is also working on a national certification scheme in association
with Central Pollution Control Board (CPCB) and Ministry of Environment and
Climate Change. Accurate environmental data is also important for the formulation
of regulations that can be enforced effectively to ensure a clean environment, and
this is elaborated in Chaps. 13 and 14. As environmental monitoring is a complex
issue, scientists from the metrology institute, academia, and industry need to work
in collaboration for improved measurement of hazardous emissions to ensure the
quality of life and quantification of parameters that influence climate. Moreover,
after the Climate Convention at Paris in 2015, most of the countries have agreed to
align their national environmental regulations with international agreements [55].
Therefore, to obtain reliable data for climate goals, harmonized measuring system
traceable to SI units are essential [56].

1.4.5 Sustainable Energy

In order to reduce carbon-dioxide emissions, the majority of the nation are focusing
on the production of their energy needs from renewable sources, e.g., solar, wind,
biomass, geothermal, and hydropower. However, to ensure secure and sustainable
energy resources, a national strategy needs to be evolved that would address all
aspects of the energy, including production of energy from both non-renewable and renewable, supply chain, reduction in greenhouse gas emission, ensuring the stability of power grid and to introduce methods for reducing the energy consumption, e.g., by utilizing efficient devices. In addition, research and development should continue for the development of new technologies for energy production as well as new methodologies to optimize the operation of conventional and nuclear power plants in most efficient manner. All these require a strong metrology infrastructure to ensure better quantification of measurement parameters across the full energy chain, i.e., generation, transmission, and consumption [57]. The measurement capabilities enable regulators to perform the tests for ensuring the conformity assessment of equipment and appliances for their energy efficiency. CSIR-NPL has established calibration facilities for the measurement of the efficiency of organic solar cells and details of this are presented in Chap. 16.

### 1.4.6 Facilitation of International Trade

World Trade Organization (WTO) keeps making efforts in removing technical barriers to ensure free international trade and promote free competition worldwide. Most nations adopt their standards and regulations on measuring devices to protect both manufacturers and customers in their respective countries. However, if these standards and regulations are not backed by a functioning measurement system traceable to SI units, their noncompliance can lead to technical barriers to trade. In modern time, it is normal that various components of “a system device” are manufactured in different countries, and therefore, the compatibility of components, in any case, is required even though their trade are coming under non-regulated areas of trade. Thus, in order to produce goods of high quality, nations must ensure that their measurement system is on par with an international one. As has been discussed earlier, CIPM MRA and the OIML Mutual Acceptance Arrangement (MAA) facilitate the promotion of setting up of uniform international measurement system to ensure consistency in testing for global trade. In order to eliminate the technical barriers to trade (TBT), WTO introduced TBT Agreement in 1995, which sets out a code of good practice for both governments and non-governmental or industry bodies to prepare, adopt and apply voluntary standards [58]. Removal of technical barriers to trade contribute to several benefits: (i) the time and cost of transactions are reduced; (ii) the possibilities of international trade disputes reduces; (iii) low-quality imports into the country can be minimized; and (iv) the possibility of export rejection is minimized. Therefore, a strong quality infrastructure of a country is the backbone for improving the quality of the indigenously developed products and enhance their competitiveness for global trade. This in turn builds the confidence of investors, particularly in developing countries like India, where efforts are being made to attract foreign direct investment for economic growth. A poor conformity assessment service that is not traceable to SI units can allow entry of imports that are sub-standard and toxic in nature. There are numerous cases where poor-quality import items could enter in
the country, e.g., steel, toys, tyres, light-emitting diodes (LEDs), electronic items, solar panels, food items, etc. [59–64]. These poor-quality imports having toxicity not only make their disposal an economic burden but also pose health hazards. Similarly, the export consignments get rejected if the quality does not pass through the conformity assessment of the importing country [65–67]. Therefore, the country must have a strong quality-infrastructure for international trade to avoid huge economic losses. As discussed above, BNDs are utilized to calibrate the analytical equipment of testing laboratory, and the details of the BND program (production to marketing) are discussed in Chaps. 18 and 19. In fact, the theme for World Metrology Day 2020 was “Measurements for Global Trade”, which was chosen to create awareness of: (i) importance of measurement in enabling a fair global trade. (ii) measurements ensure that products meet standards and regulations, and (iii) measurements safeguard the quality expectations of customers.

1.4.7 Creating a Level Playing Field in Society

Accurate measurements in day to day activities, safeguarded through national quality-infrastructure, generate a state of affairs in the society in which every citizen gets a fair deal. This can be achieved if all the regulators (as mentioned in Table 1.1) in their domain ensure that all the measuring instruments, e.g., electronic instruments, weighbridges, petrol pumps, water meter, sphygmomanometer, clinical thermometer, medical equipment, scientific instruments, etc. are calibrated periodically. The accurate measurement values of these instruments are used by traders, industries, hospitals, academia, and other organizations are essential to ensure that common citizens are not cheated, e.g., the farmers producing the food commodities, milk, etc. get the values worth their products, the consumer gets the right amount of the quantity for their money, the trucks carry the right kind of load to avoid damage to the roads, the doctors measure correct values of body parameters for medical diagnosis of poorest of the people enabling to save their hard-earned money, customers get the right quantity in the prepacked food items, etc. Measurements traceable to SI units create trust in the society and benefit one and all. The significance of accurate measurements in a developed society is evident when a Japanese rail company expressed regret after a train left a station 25 s early in May 2018 and the second similar incidence happened again after 8 months. The society felt that the mistake is truly inexcusable and customers are faced with slipping standards of the Japanese rail company [68].

1.5 Digital SI units

As highlighted earlier, Industry 4.0 will require the new digital metrology. This implies that measured values obtained from different sub-components are converted into reliable machine-readable digital data. High-quality digital data as well as their
exchange also are the foundation for reaping benefits of artificial intelligence and machine-learning applications. To establish the concepts of digital metrology, the International Committee for Weights and Measures has already set up a Task Force on “Digital SI” (D-SI) and authorized to develop a world-wide harmonized, unambiguous, and secure basic standard for measurement data exchange, i.e., transformation of the SI units into a meta-data format for digitized world [69]. The meta-data format of metrology would require complete coverage of the information, i.e., the numerical value of a measured quantity, assigned SI unit, measurement uncertainty, timestamp, etc. It is expected that D-SI will be established in the coming years and will give a new fillip to cyber-secure digital science and technology.

1.6 CSIR-NPL in Service of Nation

CSIR-NPL through its primary/national calibration facilities supports thousands of quality-assurance testing and calibration laboratories across the country, which belong to the government, strategic sector, industries, etc. Detailed analysis of these services is presented in Chap. 21. In addition, CSIR-NPL also supports NMIs of the South Asian Association for Regional Cooperation (SAARC) nations. CSIR-NPL is the “Timekeeper of the Nation” and generates Indian Standard Time (IST) traceable to Coordinated Universal Time (UTC). CSIR-NPL disseminates IST to various sectors across the country. Detailed discussion on these contributions is presented in the subsequent chapters of this book.

CSIR-NPL also develops technologies and provides consultancies to industries and the strategic sector. One of the earliest technologies developed by CSIR-NPL was the Indelible-ink—the mark of democracy, which was transferred to Mysore Varnish and Paints Ltd. (MVPL) for mass production [72]. During elections, the purple ink is applied to the forefinger of voters, as shown in Fig. 1.15a, to prevent electoral fraud, e.g., multiple voting and malpractices. MVPL exports the indelible ink to several countries like Thailand, Nigeria, Singapore, South Africa, Malaysia, etc. CSIR-NPL has developed technologies and provided several consultancy services in the areas of strategic sectors, societal, environmental, energy, biomedical, and n-Cov19 related, e.g., ultraviolet disinfectant products, contactless thermometers, calibration services to ventilators and personal protection equipment, etc.

Another great contribution of CSIR-NPL is the preservation and maintenance of the “Original Copy of the Constitution of India” which is kept at Parliament Library, New Delhi, see Fig. 1.15(b) [73]. For this CSIR-NPL designed and developed two hermetically sealed glass cases in association with Getty Conservation Institute, USA. On 26 November 1949, the Constituent Assembly adopted “Constitution of India” written under the chairmanship of B. R. Ambedkar, which came into force on 26 January 1950. The original copy of the constitution of India has two following versions.
Fig. 1.15  Shri Narendra Modi, Prime Minister of India, a displaying the mark of indelible-ink developed by CSIR-NPL and manufactured by Mysore Paints and Varnish Ltd. Photo courtesy Ref. [70], b paying respect to the “Original copy of the Constitution of India” (Hindi and English versions) at Parliament Library, preserved in hermetically sealed cases developed by CSIR-NPL and Getty Conservation Institute, USA. Photo courtesy Ref. [71]

(i) English version: Calligraphed by Prem Behari Narain Raizada. It consists of 221 pages of hand-made parchment paper of size $45.7 \, \text{cm} \times 58.4 \, \text{cm}$ and weighs ~13 kg. The decoration of these sheets was done by Nand Lal Bose, which depicts a journey from the Mohen-jo-Daro and Vedic periods to the Indian freedom movement.

(ii) Hindi version: comprises 252 calligraphed sheets and weighs ~14 kg, and was calligraphed by Basantrao Vaidya almost similar to the English version.

Both documents are bound in first-class Morocco leather embossed in gold. These original calligraphed copies of the ‘Constitution of India’ are kept in the Parliament Library, and have great autographic and historical value as they contain the signatures of the founding fathers of the Constitution. The preservation of these prestigious documents is being done by the scientists of CSIR-NPL.

CSIR-NPL also provides training programs in the areas of metrology and quality assurance for the personnel of industries and regulators. In addition, CSIR-NPL has a diploma program on “Precision Measurement and Quality Control, (PMQC)” and offers Ph.D. programs on metrology and advance topics of research. The details on various training programs of CSIR-NPL on skill development are presented in Chap. 20.
1.7 Summary

A hard work on world metrology for more than 140 years has resulted in SI units that are defined in terms of fundamental constants of nature. The advantages of revised SI units are that they are sustainable infinitely and would drive innovation for future technologies. The D-SI is expected to be established soon, which will benefit the world economy through secure digitalization. The CSIR-NPL, as the NMI of India, not only has been participating and contributing to the BIPM and APMP but also realized many CMCs for the country. The metrological trackabilities’ are being disseminated to various stakeholders across the county either directly or through Legal Metrology and NABL accredited laboratories. Analyses of various knowledge creation models, e.g., Quadruple and Quintuple Helix models indicated that these models are inadequate to be implemented in the developing countries as they lack in explaining the underlying binding forces among the four helices namely government, industries, academia, and society. The Aswal model of inclusive growth suggests that metrology ensured through national quality infrastructure fortifies interactions amongst the four helices. An analysis of national quality infrastructure in India revealed that it requires to be strengthened to realize the goals of self-reliance. The metrology plays a key role in improvising the technology development and industrialization, cyber-physical systems and cybersecurity, affordable healthcare and safety, clean environment and climate change, sustainable energy, facilitation of international trade, and creation of a level playing field in the society.

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