# 4

# Metrology

## INTRODUCTION

Metrology is the science of measurement, and it is arguably the oldest of the three fundamentals of the quality infrastructure (QI); the other two, standardization and accreditation, are much younger. The first record of a permanent measurement standard was in 2900 BC, when the royal Egyptian cubit was carved from black granite. The cubit was decreed to be the length of the pharaoh's forearm plus the width of his hand, and replica standards were given to builders. The success of a standardized length for the building of the pyramids is indicated by the lengths of their bases differing by no more than 0.05 percent.

Today, metrology permeates every area of human endeavor, and it is virtually impossible to describe anything without referring to weights and measures. Products are bought by size, weight, and volume; production processes are regulated by measurements; health care relies on measurements; science is totally dependent on metrology—the list can go on and on. Metrology has developed into one of the most sophisticated sciences, a science in which cooperation across the world is absolutely essential to maintain modern technology.

## 4.1 HISTORY

Since time immemorial, agreed-on units of measurement for quantities such as length, weight, and volume were in use for fair trade and for building and construction. Some impressive examples include the cubit from the third millennium BC, which was found in the remains of an ancient Mesopotamian temple, and the renowned royal cubit of the Egyptians, which was used as the basic length measure for building the Egyptian pyramids dating to about 350 BC. Distance was indicated in the Roman Empire by the *mille passuum* (a thousand paces), consisting of eight *stadiums*, and was calculated on the basis of 5 Roman feet (each ± 296 millimeters) to the *pace* (± 1.48 meters). The *libra* was a weight measure in the Roman Empire (about 327.5 grams) divided into 12 *unciae* for smaller quantities.

It was not only trade that required a uniform set of weights and measures. The fear of invasions, the desire of rulers to extend their power, and wars also contributed. Qin Shi Huang, who built the Great Wall of China to keep the Tatars out, announced a set of weights and measures for all the tribes in his empire in about 220 BC to consolidate his rule. After the collapse of these empires and the Dark Ages that followed, much measurement knowledge and standardization were lost. Although local systems of measurement were common, comparability was difficult because many local systems were incompatible. England established the Assize of Measures to create standards for length measurements in 1196, and the 1215 Magna Carta included a section for the measurement of wine and beer. Charlemagne, William the Conqueror, and the French politician Talleyrand all tried to introduce a uniform system of measurement, but none survived.

Modern metrology has its roots in the French Revolution. With a political motivation to harmonize units throughout France, a length standard based on a natural source was proposed, and in 1791 the meter was defined. This led to the creation of the decimal-based metric system in 1795, establishing standards for other types of measurements. Several countries adopted the metric system thereafter. In 1875, a diplomatic conference on the meter took place in Paris, and an international treaty, the Metre Convention, was signed that established the metric system. The metric system was modernized in 1960 with the creation of the International System of Units (SI) as a resolution at the 11th General Conference on Weights and Measures (CGPM).

## 4.2 DEFINITION AND SCOPE

### 4.2.1 Definition

Metrology is "the science of measurement and its application" (BIPM 2012), embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology. Metrology consists of three main tasks:

- The definition of internationally accepted units of measurement
- The realization of the units of measurement by scientific methods in measurement standards
- Traceability, linking measurements made in practice to measurement standards

### 4.2.2 Metrology categories

Metrology is generally separated into three categories with different levels of complexity, accuracy, and outcome:

- *Scientific metrology* at the highest level is concerned with the establishment of units of measurement, the development of new measurement methods, the realization of measurement standards, and the transfer of traceability from these standards to users in a society.[1] At a lower level, it is mostly concerned with the establishment and maintenance of national measurement standards.
- *Legal metrology* concerns activities that result from regulatory requirements regarding measurement units, instruments, and methods. Such regulatory

requirements may arise from the need for protection of consumers and to safeguard fair trade, protection of health and the environment, public safety, and enabling taxation.

- *Industrial metrology,* also known as applied or technical metrology, is concerned with the application of measurements to manufacturing and other processes and their use in society, ensuring the suitability of measurement instruments, their calibration, and quality control. Industrial metrology is important for a country's economic and industrial development, and the condition of a country's industrial metrology program can indicate its economic status.

## 4.3 SCIENTIFIC METROLOGY

### 4.3.1 Fields of scientific metrology

Under the Metre Convention, which addresses scientific metrology, there are seven base units: *mole* (dealing with amount of substance—that is, chemical and increasingly biological metrology); *ampere* (electricity and magnetism); *meter* (length); *kilogram* (mass); *candela* (photometry and radiometry); *kelvin* (thermometry); and *second* (time and frequency).

Among the consultative committees (CCs) of the International Committee for Weights and Measures (CIPM), these seven base units are complemented by two further CCs: one for acoustics, vibration, and ultrasound; and a second one for ionizing radiation and radioactivity. There is one cross-cutting CC among all nine base units: the Consultative Committee for Units (CCU).

### 4.3.2 Measurement standards

A measurement standard, or etalon, for physical metrology or a higher-order method in metrology in chemistry is a material measure, measuring instrument, reference material, or measuring system intended to define, realize, conserve, or reproduce a unit or one or more values of a quantity to serve as a reference.

For example, the meter is defined as the length of the path traveled by light in vacuum during a time interval of 1/299,792,458th of a second. The meter may be realized at the primary level with the help of the wavelength from an iodine-stabilized helium-neon laser. On a secondary level, material measures like gauge blocks may be used, and traceability can be ensured by using optical interferometry to determine the length of the gauge blocks with reference to the above-mentioned laser light wavelength.

The different levels of measurement standards are shown in figure 4.1. For each measurement quantity within the metrology fields and subfields (table 4.1), a variety of measurement standards can be used to establish traceability.

### 4.3.3 Metrology in chemistry

Metrology has developed from physical measurements and emphasizes results traceable to defined reference standards—normally the International System of Units (SI)—with known uncertainties. With the increase in world trade and the imposition of technical regulations regarding safety and health issues and protection of the environment, metrology in chemistry has grown in importance in

**TABLE 4.1 Subject fields of metrology**

| SUBJECT FIELD | SUBFIELDS |
|---|---|
| Mass and related quantities | Mass measurement |
| | Force and pressure |
| | Volume and density |
| | Viscosity |
| Electricity and magnetism | Direct current electricity |
| | Alternating current electricity |
| | High-frequency electricity |
| | High current and high voltage |
| Length | Wavelength and interferometry |
| | Dimensional metrology |
| | Angular metrology |
| | Forms |
| | Surface quality |
| Time and frequency | Time measurement |
| | Frequency |
| Thermometry | Temperature measurement by contact |
| | Noncontact temperature measurement |
| | Humidity |
| | Absorbed dose—medical products |
| | Radiation protection |
| | Radioactivity |
| Photometry and radiometry | Optical radiometry |
| | Photometry |
| | Colorimetry |
| | Optical fibers |
| Flow | Gas flow (volume) |
| | Flow of liquids (volume, mass, and energy) |
| | Anemometry |
| Acoustics, ultrasound, and vibration | Acoustical measurement in gases |
| | Accelerometery |
| | Acoustical measurements in liquids |
| | Ultrasound |
| Chemistry | Environmental chemistry |
| | Clinical chemistry |
| | Materials chemistry |
| | Food chemistry |
| | Biochemistry |
| | Microbiology |
| | pH measurement and electrical conductivity |

*Source:* EURAMET 2008.
*Note:* The subject fields shown in this table do not correspond directly with the subject fields of the various International Bureau of Weights and Measures (BIPM) consultative committees, which are more science-oriented, but this list may be more appropriate for determining the needs of low- and middle-income countries.

recent times. Typically, chemical measurements are more complex than physical measurements because of more complex measurement conditions and matrix effects (table 4.2).

Metrology in chemistry can be seen as consisting of (a) the development of reference methods, mainly matrix independent; (b) the production of certified

**TABLE 4.2 Metrology in physics and chemistry: Similarities and differences**

| CHARACTERISTIC | PHYSICS | CHEMISTRY |
|---|---|---|
| Measurement | Comparing a quantity (for example, temperature) | Comparing a quantity (for example, DDT in milk) |
| Units | m, s, kg | mol/kg, mg/kg |
| Influenced by | Relies mostly on direct measurements | Various factors influence the measurement results |
| Main impact | Equipment calibration | Chemical treatment (for example, extraction, digestion); reference materials used; and equipment calibration |
| Depends on | Largely sample independent | Strongly sample dependent |
| Example | Length of a table | Concentration of lead in seawater, soils, blood, and so on |

*Source:* EURAMET 2008.
*Note:* DDT = dichlorodiphenyltrichloroethane; kg = kilogram; m = meter; mg/kg = milligrams per kilogram; mol/kg = mole per kilogram; s = second (see further definitions in table 4.3).

reference materials; and (c) the provision of proficiency schemes—all at a higher level to serve as national measurement standards in chemistry in support of agriculture, chemicals, energy, climate change and clean air, food safety, health and environment, pharmaceuticals, metals, law enforcement, and the manufacturing and mining industries.

### 4.3.4 Certified reference materials

A certified reference material (CRM) is a reference material for which one or more of its property values are certified by a procedure that establishes traceability to a realization of the unit in which the property values are expressed. Each certified value includes an uncertainty statement.[2] CRMs are generally prepared in batches and have expiration dates. The property values are determined within stated uncertainty limits by measurements on samples representative of the whole batch.

## 4.4 LEGAL METROLOGY

Legal metrology is the second category of metrology. It originated from the need to ensure fair trade, specifically in the area of weights and measures, and is still known as trade metrology in some countries. Legal metrology is primarily concerned with measuring instruments, and its main objective is to assure citizens of correct measurement results when used for official measurements and commercial transactions. These would include trade and law enforcement. A legal metrology system generally comprises four interrelated elements:

- Type approval or conformity assessment of measuring equipment
- Calibration and verification of measuring equipment in use
- Market surveillance of measuring equipment falling within the scope of regulation
- Prepackaging controls of prepackaged goods

All of these have to be appropriately defined and given legitimacy in legal metrology legislation and regulations. Legal metrology is therefore part and parcel of a technical regulation regime and has to comply with the World Trade Organization (WTO) Agreement on Technical Barriers to Trade (TBT Agreement) requirements (see module 7: Technical Regulation) if the country is a WTO member.

In addition to trade-related issues, there are fields under regulation that require metrology, many of them to protect the health and safety of individuals, fauna and flora, and the environment. In the European Union, for example, more than 80 different regulations and directives involve metrology, such as the Water Framework Directive, the In Vitro Diagnostic Regulation, the European Atomic Energy Community (Euratom) Basic Safety Standards Directive, and others.

## 4.5 INDUSTRIAL METROLOGY

Industrial metrology, also known as applied or technical metrology, is concerned with the application of measurements to manufacturing and other processes and their use in society, ensuring the suitability of measurement instruments, their calibration, and quality control. Although the emphasis in this area of metrology is on the measurements themselves, traceability of the measuring device through calibration is absolutely necessary to ensure confidence in the measurement. Systematic measurement with known degrees of uncertainty is one of the foundations of quality control, and in modern industries the costs bound up in taking measurements can constitute 10–15 percent of production costs (EURAMET 2008). Industrial metrology is therefore important for a country's economic and industrial development, and the state of a country's industrial metrology program can indicate its economic development status.

The normal development in industrial economies and in many emerging economies has been a bottom-up approach. A country's national metrology institute (NMI) starts with low-level but traceable, recognized calibrations for industry, and in parallel it promotes independent (largely private) calibration laboratories by transferring knowledge and procedures and assuring traceability. As the NMI and independent calibration laboratories develop competences, the NMI withdraws its calibration service over time from the market to concentrate its resources on scientific metrology, focusing on the development of new metrological services for the benefit of users and the economy. The calibration of industrial measuring equipment then increasingly becomes the purview of the independent calibration laboratories or of major industries or organizations that establish the same in-house.

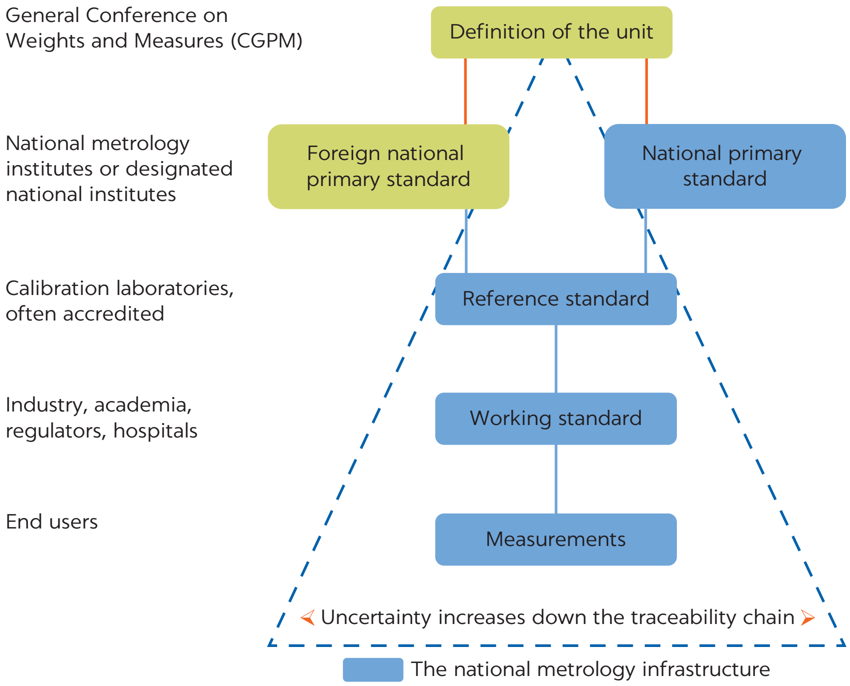
## 4.6 THE TRACEABILITY CHAIN AND MEASUREMENT UNCERTAINTIES

### 4.6.1 Traceability

A traceability chain is an unbroken chain of calibrations, all having stated measurement uncertainties (figure 4.1). This ensures that a measurement result or a standard is referenced to a standard at a higher level, ending at a primary standard that is a physical realization of the international definition of the unit. In chemistry and biology, traceability is often obtained by using CRMs and

FIGURE 4.1

**The traceability chain in metrology**




*Source:* EURAMET 2008. ©European Association of National Metrology Institutes (EURAMET). Reproduced with permission from EURAMET; further permission required for reuse.

reference procedures ending at a higher-order method or reference material representing the best possible realization of the chemical measurand.

An end user may obtain traceability to the highest international level either directly from an NMI or via a secondary accredited calibration laboratory (as further discussed in section 4.12). Different primary standards are compared on an international level.

## 4.6.2 Calibration

Measuring instruments or systems are not always accurate, nor do they maintain their accuracy over time, because of influences of the environment to which they are exposed, wear and tear, and overload or improper use. Hence, they have to be calibrated from time to time to determine their current accuracy and ensure that their results are traceable to known measuring standards. That is, calibration determines the performance characteristics of an instrument, system, or reference material.

Calibration is usually achieved by means of a direct comparison against measurement standards, CRMs, or a higher-order reference method, all of which have a smaller measurement uncertainty than the unit to be calibrated. There are four main reasons for having an instrument calibrated:

- To establish and demonstrate traceability
- To ensure that readings from the instrument are consistent with other measurements (comparability of measurements)
- To determine the accuracy of the instrument readings
- To establish the reliability of the instrument—that is, that it can be trusted

### 4.6.3 Measurement uncertainty

All measurements are subject to fluctuations or systematic errors, in that the result of a measurement differs from the true value of the unit measured. Measurement uncertainty is a quantitative measure of the quality of a measurement result, enabling the measurement results to be compared with other results, references, standards, or regulative requests.

## 4.7 THE NECESSITY AND IMPACT OF METROLOGY

### 4.7.1 Economic necessity and benefits

There are four main areas in which metrology has important economic effects, even in the short term (Swann 2009).

**Metrology can increase the productivity of organizations.** Increased productivity was first seen in the 18th and 19th centuries with the development of interchangeable parts; this became an important aspect of the so-called American system of manufacturing. The use of precise measurement revolutionized interchangeable manufacture because it enabled an effective and efficient division of labor. Later, measurement became one of the integral parts of process control and continues to be integral to advanced manufacturing. The more precise the measurement and the faster the feedback from measurement to control, the greater the effects on efficiency, quality, and productivity. In modern industries, metrology is considered to represent about 10–15 percent of production costs (EURAMET 2008).

**Metrology supports innovation.** The Wright brothers used measurement as part of their research into the aerodynamics of aircraft wings and, building on that, as part of their development effort to build the first viable airplane. More modern examples include the publicly funded metrology activities that helped to support innovation by Rolls-Royce and Boeing.

Measurement is also important to the innovator because it offers an objective way to demonstrate to customers that an innovative product is indeed superior to the competition. In the absence of any such measurements, the skeptical customer may be unconvinced, but if the superior product's characteristics can be measured in an objective (and independently verifiable) way, this supports the marketing effort of the innovative producer. In this way, measurement can play an important role in avoiding market failure for innovative new products.

Another related example is the use of measurement to demonstrate the purity and quality of premium products. The intimate relationship between measurement and innovation is illustrated by the case of a company that needed to develop its own measurement instruments to demonstrate the superiority of its products, and this was the first step in the diversification of the company from optical manufacture into instrumentation for advanced metrology (Swann 2009).

**Metrology helps to reduce the transaction costs between suppliers and customers in a market economy.** One of the most common sources of market failure is asymmetric information between buyers and sellers, where the buyer cannot distinguish good products from bad and therefore does not buy. Often this arises because measurement is difficult or expensive. As measurement improves and becomes cheaper, buyers can measure any product characteristics they wish, which eliminates asymmetric information and reduces transaction costs. In fact, many producers now use measurements of product characteristics to advertise their products.

Metrology also ensures fair trade. Both the supplier and the purchaser are protected by measuring equipment that is accurate—the purchaser by getting what is paid for, and the supplier by avoiding oversupplying or undersupplying the stated quantity of the product purchased, which in the United States amounts to about US$5 trillion in sales per year (Swann 2009).

**Metrology helps societal groups.** Many consumers are interested in careful measurement of product characteristics to ensure quality, safety, purity, dosage accuracy, and so on. These could include food composition data, the alcohol content of drinks, the sun protection factor of sunblock, the speed of a car and the temperature of its cooling system, the performance characteristics of a hi-fi stereo system, or the accurate and early detection of carbon monoxide in the home.

In the health service, clinicians depend on the precise measurement of doses, which is essential for efficacy and safety in medicines and for the diagnosis of medical conditions. They also make extensive use of measurement instruments to check patient health (for example, for blood pressure, blood tests, and so on). Such measurements are important not only in managing the health care of individual patients, but also in the context of epidemics.

Those concerned with the environment depend on measurement for accurate information about meteorological conditions (such as wind, rainfall, sunshine, and temperature); pollution and emissions (such as carbon dioxide emissions); geoseismic measures; measures of the ozone layer; measures of the condition of the polar caps; and so on. In addition, measurement has at least three important roles in education and training: as part of the curriculum, as an essential input to the research process, and in assessing student aptitude and performance.

## 4.8 SYSTEMS OF MEASUREMENT

The SI has been adopted by 59 states that are signatories to the Metre Convention and additionally by 42 associate states and economies. Together they represent more than 98 percent of worldwide gross domestic product (GDP).

In some countries, special units such as those known as imperial units (for example, in the United Kingdom and the United States) are allowed by their governments. These are used either in addition or as an alternative to the SI. It should be noted, however, that in these alternative systems the conversion factors to the SI are fixed and agreed upon. So, scientifically, they can be considered as alternative ways of expressing measurement that are still consistent with the SI.

### 4.8.1 The International System of Units (SI)

The SI, consisting of seven base units and units derived from them, is a fully coherent system.[3] It developed out of the metric system, which had been in place since 1875. The SI system was established as a decision of the 11th General Conference on Weights and Measures (CGPM) in 1960 (as discussed earlier in section 4.3), during which six units were introduced as base units: the kilogram, meter, second, ampere, kelvin, and candela. During the 14th CGPM (1972), the mole was added as the seventh base unit.

The CGPM approved a redefinition of the SI base units during the 26th CGPM in November 2018, to come into force as of World Metrology Day, on May 20, 2019. These redefinitions are based on the idea to define all seven base units by fixing the numerical value of a natural constant, as was already done for the definition of the second and the meter. The four base units kilogram, ampere, kelvin, and mole are redefined in terms of fixed numerical values of the Planck constant ($h$), the elementary charge ($e$), the Boltzmann constant ($k$), and the Avogadro constant ($N_A$), respectively. In addition, the luminous efficacy is used to define the candela. The seven SI base units are listed in table 4.3 with their 2018 definitions (BIPM 2018).

A few examples of derived units based on SI base units are shown in table 4.4. Some coherent derived units have been given special names. A few examples of these are shown in table 4.5.

The SI also includes rules for prefixes, prefix symbols, and the writing of SI unit names and symbols. Table 4.6 provides an overview of the prefixes. Rules for writing the SI can be found in a number of publications, notably those of the International Bureau of Weights and Measures (BIPM 2008).

Quite a number of non-SI units are used. These include units such as time (for example, minute or hour); plane angle (degree, minute, and second); volume (such as liter); mass (such as metric ton); and pressure in fluids (such as bar). Then there are also units outside the SI that are accepted within specific subject areas: length (such as nautical mile); speed (such as knot); mass (such as carat); linear density (such as tex); pressure

**TABLE 4.3 SI base units and their definitions (valid as of May 20, 2019)**

| QUANTITY | BASE UNIT | SYMBOL | DEFINITION |
|---|---|---|---|
| Length | meter | m | The meter, 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 m/s, where the second is defined in terms of $\Delta\nu_{Cs}$. |
| Mass | kilogram | kg | The kilogram, symbol kg, is the SI unit of mass; its magnitude is set by fixing the numerical value of the Planck constant to be exactly 6.626 070 15 × $10^{-34}$ when it is expressed in the SI unit for action J s = kg $m^2$ $s^{-1}$. |
| Time | 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 $\Delta\nu_{Cs}$, 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 $s^{-1}$. |
| Electric current | 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 to be 1.602 176 634 × $10^{-19}$ when expressed in the unit C, which is equal to As, where the second is defined in terms of $\Delta\nu_{Cs}$. |
| Thermodynamic temperature | 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 $k$ to be 1.380 649 × $10^{-23}$ when expressed in the unit $JK^{-1}$, which is equal to kg $m^2s^{-2}K^{-1}$, where the kilogram, meter, and second are defined in terms of $h$, $c$, and $\Delta\nu_{Cs}$. |
| Amount of substance | mole | mol | The mole, symbol mol, is the SI unit of amount of substance. One mole contains exactly 6.022 140 76 × $10^{23}$ 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. |
| Luminous intensity | 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 $kg^{-1}m^{-2}s^3$, where the kilogram, meter, and second are defined in terms of $h$, $c$, and $\Delta\nu_{Cs}$. |

*Source:* BIPM 2018.
*Note:* SI = International System of Units.

**TABLE 4.4 Examples of SI-derived units expressed in SI base units**

| DERIVED QUANTITY (SYMBOL) | DERIVED UNIT | SYMBOL |
|---|---|---|
| Area (A) | square meter | $m^2$ |
| Volume (V) | cubic meter | $m^3$ |
| Speed, velocity (v) | meter per second | m/s |
| Acceleration (a) | meter per second squared | $m/s^2$ |
| Density, mass density (ρ) | kilogram per cubic meter | $kg/m^3$ |
| Surface density ($\rho_A$) | kilogram per square meter | $kg/m^2$ |
| Specific volume (v) | cubic meter per kilogram | $m^3/kg$ |
| Current density (j) | ampere per square meter | $A/m^2$ |
| Magnetic field strength (H) | ampere per meter | A/m |
| Amount concentration, concentration (c) | mole per cubic meter | $mol/m^3$ |
| Mass concentration (ρ, ϒ) | kilogram per cubic meter | $kg/m^3$ |
| Luminance ($L_V$) | candela per square meter | $cd/m^2$ |

*Source:* BIPM 2008.
*Note:* SI = International System of Units.

**TABLE 4.5 Examples of coherent derived SI units with special names**

| DERIVED QUANTITY | NAME | SYMBOL | EXPRESSED IN TERMS OF OTHER SI UNITS |
|---|---|---|---|
| Plane angle | radian | rad | 1 |
| Solid angle | steradian | sr | 1 |
| Frequency | hertz | Hz | $s^{-1}$ |
| Force | newton | N | $m.kg/s^2$ |
| Pressure, stress | pascal | Pa | $N/m^2$ |
| Energy, work, amount of heat | joule | J | N.m |
| Power, radiant flux | watt | W | J/s |
| Electric charge, amount of electricity | coulomb | C | s.A |
| Electric potential difference | volt | V | W/A |
| Capacitance | farad | F | C/V |
| Electric resistance | ohm | Ω | V/A |
| Luminous flux | lumen | lm | cd.sr |
| Illuminance | lux | lx | $lm/m^2$ |
| Activity referred to radionuclide | becquerel | Bq | $s^{-1}$ |

*Source:* BIPM 2008.
*Note:* SI = International System of Units; A = ampere; cd = candela; kg = kilogram; m = meter; s = second (see further definition in table 4.3); V = volt.

**TABLE 4.6 SI prefixes**

| FACTOR | PREFIX NAME | SYMBOL | FACTOR | PREFIX 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 |

*Source:* BIPM 2008.
*Note:* SI = International System of Units.

in the human body (such as millimeters of mercury), and so on. Full details of these and many more can be obtained from *The International System of Units (SI)* (BIPM 2006) and other relevant publications.

### 4.8.2 Imperial and U.S. customary systems

The system of imperial units, or the imperial system, is the system of units first defined in the British Weights and Measures Act of 1824, which was later refined and reduced. The system came into official use across the British Empire. By the late 20th century, most nations of the former empire had officially adopted the SI as their main system of measurement. The imperial system developed from what were first known as English units, as did the related system of U.S. customary units. Neither is a coherent system.

These systems include length measurements such as the inch, foot, yard, and mile; volume measurements such as the fluid ounce, pint, and gallon; area as measured in square inches or acres; and so on. Although the United Kingdom and the United States have officially adopted the SI, there are still many day-to-day instances of the use of the imperial quantities. These include road signs, milk and beer sold by volume, clothing sizes, and quite a few others.

As part of the European Union, the United Kingdom had to implement the SI in trade, especially in prepackaging. Some traders, however, resisted "metrication" and still insist on using only imperial units. Industry, except the railways other than the Channel Tunnel, has largely converted to the SI, arguing that customers in the rest of the world use it.

The United States legalized the use of the SI in 1975. Implementation, however, was never considered as a legally enforceable changeover as in other countries—for example, in South Africa in the 1970s, where the use of imperial units was banned after 1978. Hence, industry in the United States is a mixed bag. Some firms, like General Motors, changed totally to the SI, whereas others such as Boeing are still using the U.S. customary system. Consumer goods are often prepackaged with both measurements depicted on the packaging. Over time, the United States will probably gravitate more and more to the SI in everyday use as well.

## 4.9 INTERNATIONAL AND REGIONAL METROLOGY ORGANIZATIONS

At the international level, two organizations dominate: the BIPM and the International Organization of Legal Metrology (OIML). At the regional level, the situation can become quite murky, with regional metrology organizations (RMOs) representing major regions and recognized as such by the BIPM and subregional metrology organizations established as an outcome of political decisions to harmonize metrology activities within an emerging common market. Some of the latter are recognized as RMOs; others are not.

### 4.9.1 The Metre Convention and the BIPM

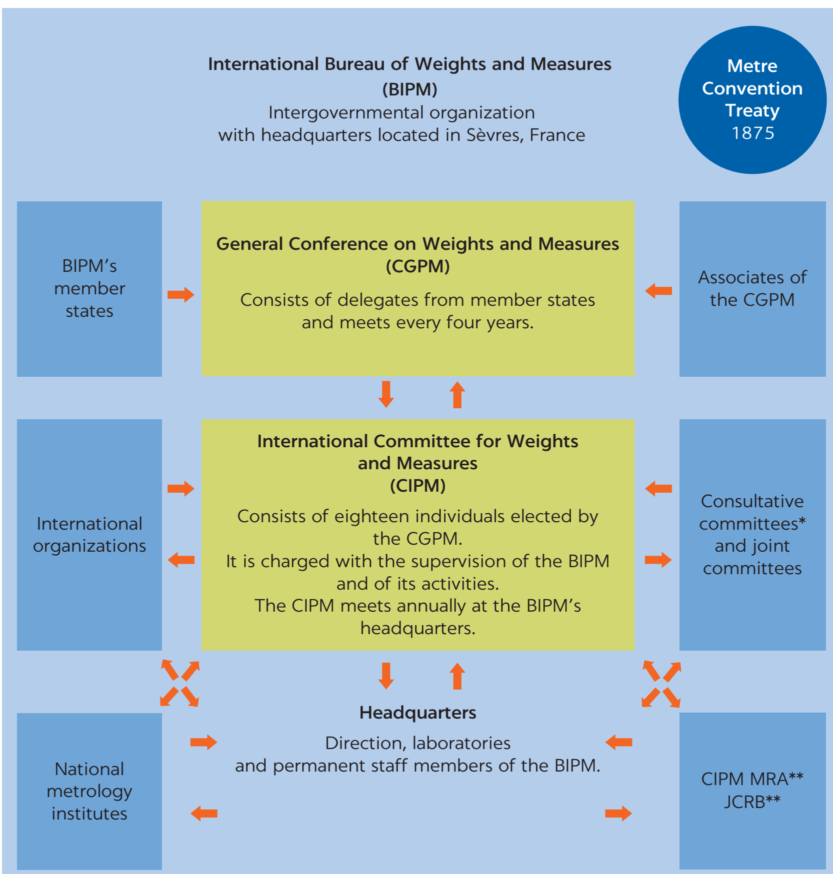
In 1875, a diplomatic conference on the meter took place in Paris, where 17 governments signed a diplomatic treaty, the Metre Convention. The signatories decided to create and finance a permanent scientific institute, the "Bureau international des poids et mesures" (BIPM). The Metre Convention was slightly modified in 1921. Presently, it has 59 member states and 42 states and economies that are associates of the CGPM, with the right to attend the CGPM as observers. The organizational structure established by the Metre Convention is shown in figure 4.2.

Representatives of the governments of the member states meet every fourth year for the CGPM. The last meeting at the time of this writing was the 26th meeting, held in November 2018. The CGPM discusses and examines the work performed by NMIs and the BIPM and makes recommendations on new fundamental metrological determinations and all major issues of concern to the BIPM. The CGPM elects up to 18 representatives to the International Committee for Weights and Measures (CIPM), which meets annually.

The CIPM supervises the BIPM on behalf of the CGPM and cooperates with other international metrology organizations. The CIPM undertakes preparatory work for technical decisions to be made by the CGPM. The CIPM is supported by 10 consultative committees. The president of each of the consultative committees is usually a member of the CIPM. The other members of the consultative committees are representatives of the NMIs and other experts.

**FIGURE 4.2**

**The Metre Convention organization**




*Source:* BIPM 2006. ©International Bureau of Weights and Measures (BIPM). Reproduced with permission from BIPM; further permission required for reuse.

*Note:* CEN = European Committee for Standardization; IEC = International Electrotechnical Commission; ISO = International Organization for Standardization; SI = International System of Units.

* There are currently 10 CCs which advise the CIPM and the Headquarters, for example, on technical matters, and the administration of CIPM MRA.

**The JCRB refers to the Joint Committee of the Regional Metrology Organizations and the BIPM.

Joint committees of the BIPM and other international organizations have been created for particular tasks:

- International Network for Quality Infrastructure (InetQI)
- Joint Committee for Guides in Metrology (JCGM)
- Joint Committee of the Regional Metrology Organisations and the BIPM (JCRB)
- Joint Committee on Traceability in Laboratory Medicine (JCTLM).

### 4.9.2 Regional metrology organizations

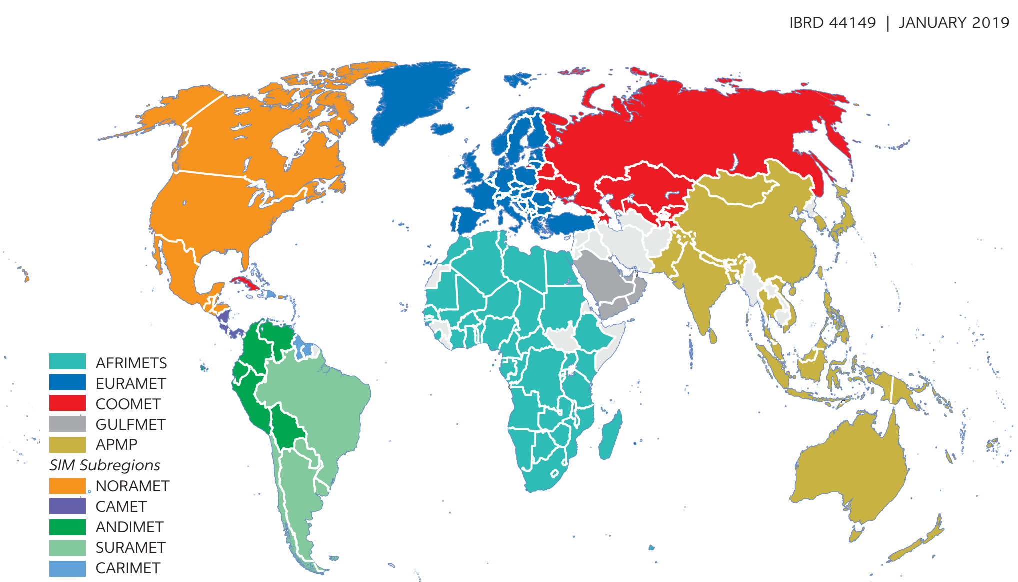
The collaboration of NMIs at regional levels is coordinated by RMOs (map 4.1). The activities of the RMOs include the following:

- Coordination of comparisons of national measurement standards and other activities of the CIPM Multilateral Recognition Agreement (CIPM MRA)
- Cooperation in metrology research and development
- Facilitation of traceability to primary realizations of the SI
- Cooperation in developing metrological infrastructure of the member countries
- Joint training and consultation
- Sharing of technical capabilities and facilities.

Within the CIPM MRA, the RMOs play a crucial role, as it is their responsibility to carry out major elements of the review process of member states of the BIPM and associate states and economies of the CGPM in respect to

**MAP 4.1**

**Regional metrology organizations**




*Source:* World Bank, from organization membership data.
*Note:* AFRIMETS = Intra-Africa Metrology System; ANDIMET = Andean Region Metrology; APMP = Asia Pacific Metrology Programme; CAMET = Central American Metrology; CARIMET = Caribbean Metrology; COOMET = Euro-Asian Cooperation of National Metrological Institutions; EURAMET = European Association of Metrology Institutes; GULFMET = Gulf Association for Metrology; NORAMET = North American Metrology Cooperation; SURAMET = South American Metrology; SIM = Inter-American Metrology System.

the CIPM MRA (as discussed in section 4.9.1) and to report their results to the Joint Committee of Regional Bodies (JCRB). At the time of this writing, six RMOs were recognized by the BIPM (map 4.1):

- Intra-Africa Metrology System (AFRIMETS)
- Asia Pacific Metrology Programme (APMP)
- Euro-Asian Cooperation of National Metrological Institutions (COOMET)
- European Association of Metrology Institutes (EURAMET)
- Gulf Association for Metrology (GULFMET)
- Inter-American Metrology System (SIM), which is organized in five subregions: NORAMET, CARIMET, CAMET, ANDIMET, and SURAMET

### 4.9.3 Other regional metrology coordination committees and bodies

In addition to these recognized RMOs, regional metrology coordination committees or bodies have been established as the outcome of trade agreements leading to regional common markets. Typical examples are found in the common markets that are emerging in Africa: the Southern African Development Community (SADC), East African Community (EAC), and Economic Community of West African States (ECOWAS). All of these African subgroupings, however, are part of AFRIMETS. These should not be confused with the RMOs recognized by the BIPM.

In many cases, NMIs and legal metrology organizations are members, having to represent their countries in these regional structures. They have no choice in the matter. Some of these regional metrology structures have full-time staff and premises; others are liaison-type committees with only a secretariat. Some of these operate as regional metrology institutions and establish and maintain regional measurement standards as a service to smaller member countries that are not able to do so. Some are forums where a regional approach to metrology is discussed and agreed to; some only coordinate metrology development activities across the region. There is no one model that is superior to others (Kellermann and Keller 2014).

## 4.10 INTERNATIONAL RECOGNITION SYSTEMS

### 4.10.1 The CIPM Mutual Recognition Arrangement

The CIPM Mutual Recognition Arrangement (CIPM MRA) is the framework through which NMIs demonstrate the international equivalence of their measurement standards and the calibration and measurement certificates they issue. The outcomes of the arrangement are the internationally recognized (peer-reviewed and approved) calibration and measurement capabilities (CMCs) of the participating institutes. Approved CMCs and supporting technical data are publicly available from the CIPM MRA's Key Comparison Database (KCDB). The CIPM MRA has been signed by the representatives of 103 institutes—from 58 member states, 41 associates of the CGPM, and 4 international organizations (the International Atomic Energy Agency [IAEA], the World Meteorological Organization [WMO], the European Space Agency [ESA], and the Joint Research Centre [JRC])—and it covers a further 157 institutes designated by the signatory bodies.

The RMOs play an important role in the CIPM MRA. The RMOs are responsible for carrying out comparisons and other activities within their regions to support mutual confidence in the validity of the calibration and measurement certificates of their member NMIs. Through the Joint Committee of the RMOs and the BIPM (JCRB), they carry out an interregional review of declared capabilities before approved CMCs are published in the KCDB, and they make policy suggestions to the CIPM on the operation of the CIPM MRA.[4]

The two preconditions for participating as an NMI in the CIPM MRA are as follows: (a) the country must be a member state of the BIPM or an associate member and economy of the CGPM, and (b) an RMO must be in place through which to submit its CMCs for consideration. Hence, for countries unable to meet these preconditions, accreditation is the only feasible way to gain some recognition until they both become a signatory or associate member and establish an RMO that is recognized by the BIPM.

### 4.10.2 Accreditation

Under the CIPM MRA, a working quality management (QM) system according to ISO/IEC 17025 has to be demonstrated (ISO and IEC 2017). This can be done through either self-declaration or accreditation. Calibration laboratories on the secondary level are accredited, because the choice of self-declaration is open only for NMIs or designated institutes.

## 4.11 THE INTERNATIONAL ORGANIZATION OF LEGAL METROLOGY (OIML)

The International Organization of Legal Metrology (OIML) is an intergovernmental treaty organization established in 1955 on the basis of a convention, which was modified in 1968. The office of the OIML is in Paris.

### 4.11.1 Purpose

The purpose of the OIML is to promote the global harmonization of legal metrology procedures. In 2017, the OIML had 62 member states (states that have ratified the convention) and 64 corresponding members that joined the OIML as observers. The OIML gives effect to its purpose in the following ways:[5]

- Develops model regulations, standards, and related documents for use by legal metrology authorities and industry
- Provides mutual recognition systems, which reduce trade barriers and costs in a global market
- Represents the interests of the legal metrology community within international organizations and forums concerned with metrology, standardization, testing, certification, and accreditation
- Promotes and facilitates the exchange of knowledge and competencies within the legal metrology community worldwide
- Cooperates with other metrology bodies to raise awareness of the contribution that a sound legal metrology infrastructure can make to a modern economy

### 4.11.2 OIML International Recommendations

The OIML International Recommendations deal with elements such as (a) scope, application, and terminology; (b) metrological requirements; (c) technical requirements; (d) methods and equipment for testing and verifying conformity to requirements; and (e) test report format.

Project Groups (PGs) within the OIML's Technical Committees (TCs) and Subcommittees (SCs) develop the organization's technical publications. The International Committee of Legal Metrology (CIML), the functional decision-making body of the organization, allocates the secretariats of TCs and SCs, and the convenorships of PGs, to member states. TCs, SCs, and PGs are composed of the following:

- *Participating Members (P-Members):* Member states willing to participate actively in the work of TCs, SCs, or PGs. P-members have voting rights.
- *Observer Members (O-Members):* Member states that wish to follow the work of TCs, SCs, or PGs without voting rights. Corresponding members may also be O-Members.
- *Liaison Organizations:* Organizations interested in following the work of the TCs, SCs, or PGs.

After acceptance by a PG, draft publications are submitted to the CIML for approval, where all member states have voting rights.

### 4.11.3 The OIML Certification System

The OIML Certificate System, introduced in 1991, gives manufacturers the possibility of obtaining an OIML Certificate and a Test Report to indicate that a given instrument type complies with the requirements of the relevant OIML International Recommendations. These certificates can be used by national legal metrology agencies globally to issue national-type approval certificates, thereby avoiding multiple testing and the associated additional costs thereof.

In 2003, the OIML introduced the OIML Mutual Acceptance Arrangement (OIML MAA) as a tool to increase the level of mutual confidence provided by the OIML Certificate System. The OIML MAA was implemented in January 2005, and its purpose is to establish a worldwide multilateral arrangement that offers a wider scope than bilateral or regional arrangements.

In 2018, the single OIML Certification System (OIML-CS) was introduced to replace the former OIML certificate systems. The biggest change was the requirement for so-called Issuing Authorities to demonstrate their competence by peer evaluation or accreditation. Today the OIML-CS remains a voluntary system for issuing, registering, and using OIML Certificates of Conformity and associated OIML Type Evaluation Reports for types of measuring instruments based on the requirements of OIML Recommendations.

Certificates are issued by OIML member states that have established one or more Issuing Authorities responsible for processing applications from manufacturers wishing to have their instrument types certified. Acceptance of these certificates becomes mandatory if a country decides to become an official "utilizer" of the OIML-CS. The Issuing Authorities may send a copy of the certificates to the OIML Bureau in Paris for registration, which requires a registration fee. The list of registered certificates is published on the OIML website.[6]

## 4.12 METROLOGY ORGANIZATIONS AT THE NATIONAL LEVEL

Some countries operate a centralized metrology system with one NMI or one national legal metrology institute. Other countries operate a decentralized system with a lead NMI and additional designated institutes that hold national measurement standards in areas not covered by the NMI. The second tier of the national metrology system consists of calibration laboratories.

### 4.12.1 National metrology institutes

A national metrology institute (NMI) is an institute charged by national decision to hold (and in many cases, also develop) national measurement standards for one or more quantities.

#### *Organization and service delivery*

An NMI represents the country internationally and regionally in relation to the NMIs of other countries, the RMOs, and the BIPM. Depending on the economy and society needs, a number of NMIs undertake primary realizations of the metrological base units and derived units at the highest achievable international level, while many NMIs (typically in low- and middle-income countries) realize some units using secondary standards that are traceable to other NMIs (see also figure 4.1).

In addition to these activities, NMIs typically are responsible for the following:

- Establishment and maintenance of national measurement standards (primary or secondary) and measurement methods
- Participation in comparisons at the highest regional and international levels (see figure 4.3)
- Research in metrology and the development of new and improved measurement systems
- Dissemination of the SI units to laboratories, industry, academia, regulators, and others through calibration of their reference or working standards
- Provision of technical support to the secondary level of calibration laboratories, the industry, scientific research institutes, testing centers, and regulators in all metrology fields
- Coordination with the national accreditation body (NAB) regarding the accreditation of calibration laboratories and participation in auditing activities of the NAB
- Maintenance of a general overview of the national calibration and traceability hierarchy (that is, the country's national measurement system, as illustrated in figure 4.1)

#### *Interlaboratory comparisons*

Participation in interlaboratory comparisons provides independent verification of an NMI's measurement capability, shows a commitment to maintenance and improvement of performance, and is a prerequisite for CMC declaration and accreditation. When beginning as an NMI, the interlaboratory comparisons can still be a low-key affair, overseen by a mature NMI acting and involving a smaller number of NMIs. As the NMI develops and matures, interlaboratory comparisons become more complex technologically and there are more of them.

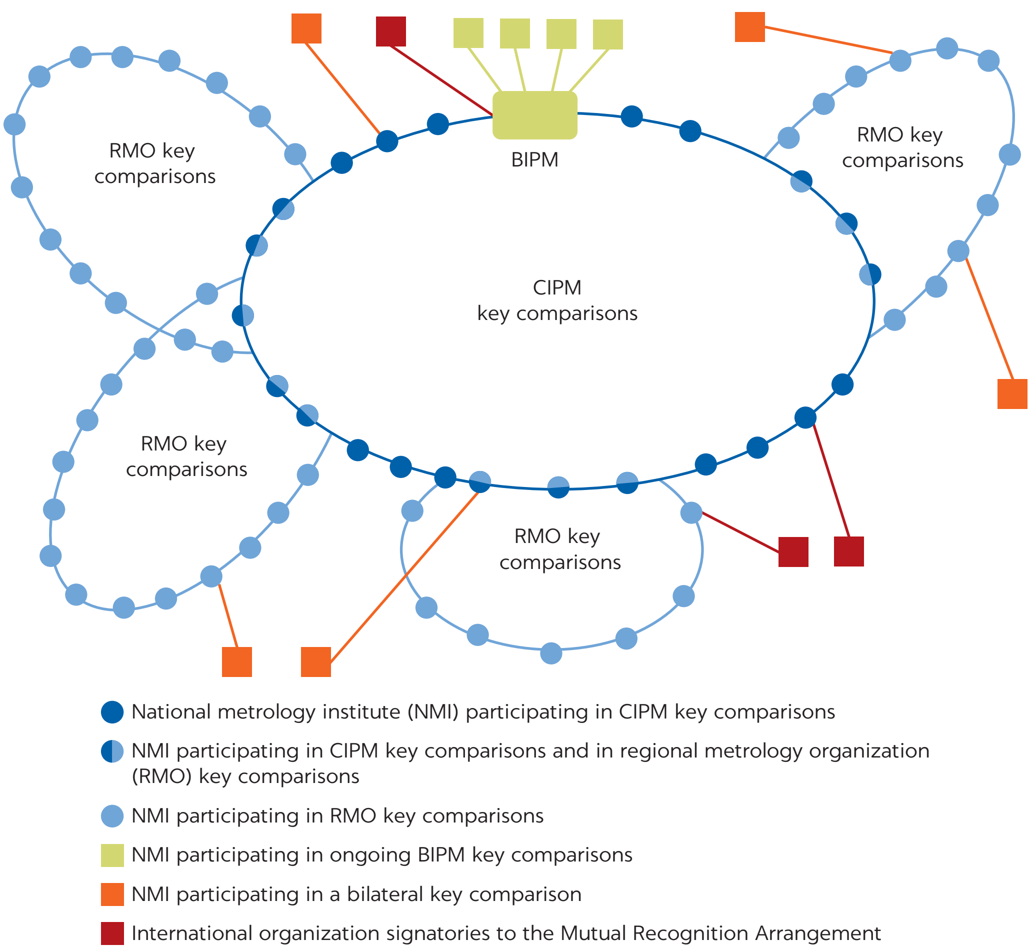
The technical basis of the CIPM MRA is the set of results obtained over time through scientific key comparisons organized by the consultative committees of the CIPM, BIPM, and RMOs; published by the BIPM; and maintained in the BIPM's Key Comparison Database (KCDB). The key comparisons are of two types:

- *CIPM key comparisons,* of international scope, are carried out by those participants having the highest level of skills in the measurement involved and are restricted to laboratories of BIPM member states. The CIPM key comparisons deliver the "reference value" for the chosen key quantity.
- *RMO key comparisons,* of regional scope, are organized at the scale of a region (though they may include additional participants from other regions) and are open to laboratories of BIPM member states as well as BIPM associates. These key comparisons deliver complementary information without changing the reference value.

The key comparisons underpin the development of the CMCs, which are stated in terms of a measured unit and its uncertainty, and may include advice about the instrumentation used. A graphical representation of the BIPM key comparison scheme is shown in figure 4.3.

**FIGURE 4.3**

**International key comparison scheme**




*Source:* BIPM 2006. ©International Bureau of Weights and Measures (BIPM). Reproduced with permission from BIPM; further permission required for reuse.
*Note:* BIPM = International Bureau of Weights and Measures; CIPM = International Committee for Weights and Measures.

### 4.12.2 Designated institutes

The NMI or its national government, as appropriate, may appoint other institutes or laboratories in the country to hold specific national standards, and these laboratories are often referred to as "designated institutes," particularly if they participate in the CIPM MRA activities.[7]

Designated laboratories should be nominated in accordance with the metrological strategy for the different subject fields and in accordance with the metrological policy of the country. As the importance of metrology increases in nontraditional areas such as chemistry, medicine, and food, fewer countries have an NMI that covers all subject fields, and hence the number of designated institutes is currently growing.

### 4.12.3 Central metrology authorities

Legal metrology is the technical regulation part of metrology. The central metrology authority in a country is usually a government organization (for example, a government department, public agency, or similar entity) because of its main responsibility, namely, ensuring that the legal metrology legislation and regulations are being followed. In high-income economies, some of the activities of the legal metrology organization (for example, calibration and verification of measuring equipment falling within the scope of legal metrology legislation) could be devolved to private sector organizations.

#### *Legislation for measuring instruments*

People using measurement instruments and results that fall within the scope of legal metrology are not required to be metrological experts, and the government takes responsibility for the credibility of such measurements. Hence, instruments falling within the scope of legal metrology legislation should guarantee correct measurement results (a) under working conditions, (b) throughout the whole period of use, and (c) within given permissible errors.

Requirements are laid down in national legislation for measuring instruments and for measurement and testing methods falling within the scope of legal metrology, including prepackaged products. It is good practice to provide for enabling legal metrology legislation as first-level legislation, which is supported by secondary-level legal metrology regulations for individual measuring equipment or prepackaging. Legal metrology legislation is normally promulgated through a parliamentary process, which then gives the relevant minister the mandate to promulgate regulations for individual instruments or prepackaging. This facilitates keeping legal metrology legislation and regulations up-to-date as technology develops. To facilitate trade within a common market, legal metrology legislation is frequently determined at the regional level for adoption and implementation at the national level.

Typical measuring equipment falling within the scope of legal metrology include the following:

- *Trade*: Scales, fuel dispensers, alcoholic spirit measures, gas flow meters, water meters, electricity meters, taxi meters, and so on
- *Safety and health:* Sound level meters, thermometers, blood pressure meters, and so on
- *Traffic law enforcement:* Speed measuring equipment, weigh bridges, tire tread gauges, breathalyzers, and so on

- *Environmental protection:* Sound level meters, gas monitoring equipment, chemical measuring equipment, and so on

Measuring equipment that should be controlled through legal metrology legislation needs to be identified for each country, and a strategy for implementing the appropriate regulations over time should be in place. Alignment of such regulations with international recommendations as published by the OIML is good regulatory practice.

#### *Type approval or conformity assessment of measuring equipment*

Preventive measures are taken before marketing of the instruments; that is, measuring instruments have to be type-approved or conformity assessed. In addition, in some countries, virtually all instruments have to be verified before use.

Manufacturers are granted type approval or conformity assessment certificates by a competent body authorized by the government once that type of instrument demonstrably meets all associated legal requirements. With serially manufactured measuring instruments, verification ensures that each instrument conforms to type and fulfills all requirements laid down in the approval procedure.[8] Alternatively, in several countries, big series of measuring instruments can be conformity assessed by proving the conformity to type based on quality assurance of the production process of the given measuring instrument. This means that the production process has to be arranged in such a way that the testing of parts during the production process leads to conforming instruments. The corresponding quality assurance system for the production process has to support and document this approach.

The certificates are normally based on the definitive description of the instrument, test reports of the instrument type, the instrument's operational instructions, and its recommended calibration intervals. In higher-income economies, the testing may be conducted in an authorized or accredited national laboratory, but low- and middle-income economies often have to rely on test reports from elsewhere, a useful source being other OIML members. Therefore, the OIML-CS, which covers different kinds of measuring instruments, represents an important tool to facilitate easier international trade of measuring instruments and helps low- and middle-income economies if they become utilizers of the OIML-CS.

#### *Market surveillance*

The government is obliged to prevent measuring instruments that are subject to legal metrology controls from being placed on the market or put into use unless they comply with legal requirements. Market surveillance is an inspection type measure used in this regard. For trade, market surveillance checks whether the only instruments being used are those that conform to the relevant legislation. For instruments in use, periodic calibration and reverifications need to be carried out to ensure that the measuring instruments continue to comply with legal requirements. Market surveillance checks whether this is the case.

Many basic consumer goods may be marketed only in specified quantities (for example, 125 gram, 250 gram, 500 gram, and 1 kilogram packaging for butter) to help purchasers make appropriate purchasing decisions. Furthermore, all prepackaged goods have to comply with the quantity (such as weight, volume, or length) as stated on the packaging within legally defined tolerance limits. During market surveillance, random checks are conducted to determine whether these measures are fulfilled by the suppliers of prepackaged goods in the marketplace.

### 4.12.4 Calibration laboratories

Measuring equipment requires recurrent calibration for a variety of reasons, whether the equipment is operated by industry, suppliers, test laboratories, regulatory authorities, or legal metrology agencies. Calibration to the secondary market (the end users of measuring equipment) can be provided by the NMI and by the legal metrology agency in the early stages of industrial development. But soon the volume of calibration work will require the establishment of secondary calibration laboratories to provide calibration services in this market. These could be independent public or private sector laboratories, or they could also be in-house entities in industry.

As independent calibration laboratories are established, the NMI's responsibilities change. The NMI should no longer be the main provider of calibration services in the secondary market but should rather support the work of the calibration laboratories. In fact, if the NMI does not disengage from its role as calibration provider in the secondary market, it will stifle the development of independent calibration laboratories. Ultimately, the calibration laboratories should provide most of the calibration services in the secondary market by far. The NMI's role to calibrate their measurement or working standards remains.

Calibration laboratories need to be able to demonstrate their technical capability. Hence, they should be accredited to ISO/IEC 17025 ("General Requirements for the Competence of Testing and Calibration Laboratories" [ISO and IEC 2017]), and their reference and working standards should be traceably calibrated to the national measuring standards. These could be either the country's own national standards or those of another country. Some calibration laboratories could also get involved in legal metrology—for example, providing calibration and verification services to users of measuring equipment that fall within the scope of legal metrology regulations. For this they would need to be designated by the legal metrology agency on fulfilling relevant requirements.

## NOTES

1. The term "fundamental metrology" is also used, and although it is formally undefined, it is considered the top level of scientific metrology, which strives for the highest degree of accuracy.
2. The term standard reference material (SRM) is also used in some parts of the world and is synonymous with a CRM.
3. When coherent units are used, equations between the numerical values of quantities take exactly the same form as the equations between the quantities themselves. Thus, if only units from a coherent set are used, conversion factors between units are never required (BIPM 2006).
4. The detailed documentation of the rules and procedures of the CIPM MRA are available from the BIPM website (http://www.bipm.org/en/cipm-mra/), as is the list of all the signatories and the complete KCDB.
5. See "What Is the OIML?" on the OIML website: https://www.oiml.org/en/about/about-oiml.

6. See the “Registered OIML Certificates” search tool: https://www.oiml.org/en/oiml-cs/certificat_view.
7. This designation should not be confused with the act of a government in “designating” an entity to provide QI services in the regulatory domain. In the case of metrology, the NMI signs the CIPM MRA and designates “other” metrology organizations (called Designated Institutions) to establish and maintain national measurement standards that it does not itself establish and maintain after signing the CIPM MRA. In the case of regulatory work, the government performs any designations because the government is ultimately accountable for the implementation of technical regulations.
8. Calibration determines the differences between the measured value, as indicated by a measuring instrument, and a measurement standard. Verification determines whether this difference falls within stated legal limits.

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