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EURAMET

Metrology in Short

Authorship and Imprint

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Authors & Contributors:

Gary Morley (NPL, UK), EURAMET Technical Committee Chairs, Participants of EURAMET TC-IM Project 1374 (BEV, Austria; CEM, Spain; DFM, Denmark; GUM, Poland; IPQ, Portugal; LNE, France), NPL, UK, and Anne Trumpfheller (EURAMET).

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EURAMET e.V.
Bundesallee 100
D-38116 Braunschweig
Germany

E-Mail: secretariat@euramet.org
Phone: +49 531 592 1960

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Guidance for Users

The 4th edition summarises the history of metrology, the worldwide measurement system, and how any measurement can be linked to any other measurement in the world through the International System of Units. A new addition is a chapter on legal metrology. The 4th edition has an expanded glossary of metrological terms, from “Absolute measurement error” to the “WTO TBT agreement” as well as an appendix on the SI, and another on how measurement uncertainty is calculated.

Further information

For further information, please visit the EURAMET website: www.euramet.org

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Chapter 1. History of Metrology

Chapter 1. History of Metrology

Introduction

Few people outside of the field itself have heard of Metrology, the scientific study of measurements, or understand what it involves. Although making measurements is something mankind has always done, it has generally been subsumed into other activities such as trade, or construction. As our social systems have evolved from small, geographically isolated communities our measurement systems have advanced along with us promoting both societal and technological development - driven by such diverse things as scientific advancement and taxation. Modern metrology has its roots in revolutionary France and is now so sophisticated that scientists have been able to link our measurement units to the fundamental physical constants of the universe itself.

1.1 Making reliable measurements - Why do we need a system of measurement units?

The benefits of metrology so pervade modern society that we do not notice its presence until it is missing.

It affects everything around us, from our transportation systems, the heating in our homes or offices, to the very food we consume.

When we buy a litre of water, we do not pause to consider that the amount in the bottle is correct. The litre we buy from a store in Berlin we *assume* is the same volume as the litre we bought in Rome; we take it for granted that these measurements are *universal*. Yet, if we think about it, how is a litre defined? How accurate is the amount of water in the bottle and who checks this or sets its value?

This principle of a common, *standardised* system of measurements underlies all worldwide trade and – as around 20 % of the European Union's (EU) Gross National Income is from international trade - even small errors can lead to significant financial cost.

It is not just trade, however, that relies on standardised measurements; they underpin all of our scientific and technological advances too. In 1999 a $125 million-dollar satellite burned up in the atmosphere of Mars. The reason was a simple measurement inconsistency. One part of the software controlling the orbital entry thrusters was calculating force using a measurement system based on pounds whilst a different algorithm was performing calculations using newtons.

It is through the work of the metrological organisations, both at the national and international level, that we can be sure of such things as what defines a litre. It is through the legislation and the regulations implemented based on their recommendations that we can be sure of the consistency of international trade and the accuracy of our scientific instruments. All of this is made possible by a measurement system formally adopted in the 1960s, the International System of Units, or SI. Since its introduction, the SI has continued to evolve and on 20th May 2019 a major worldwide change was made to the way its base units entered force to ensure its suitability in the 21st century.

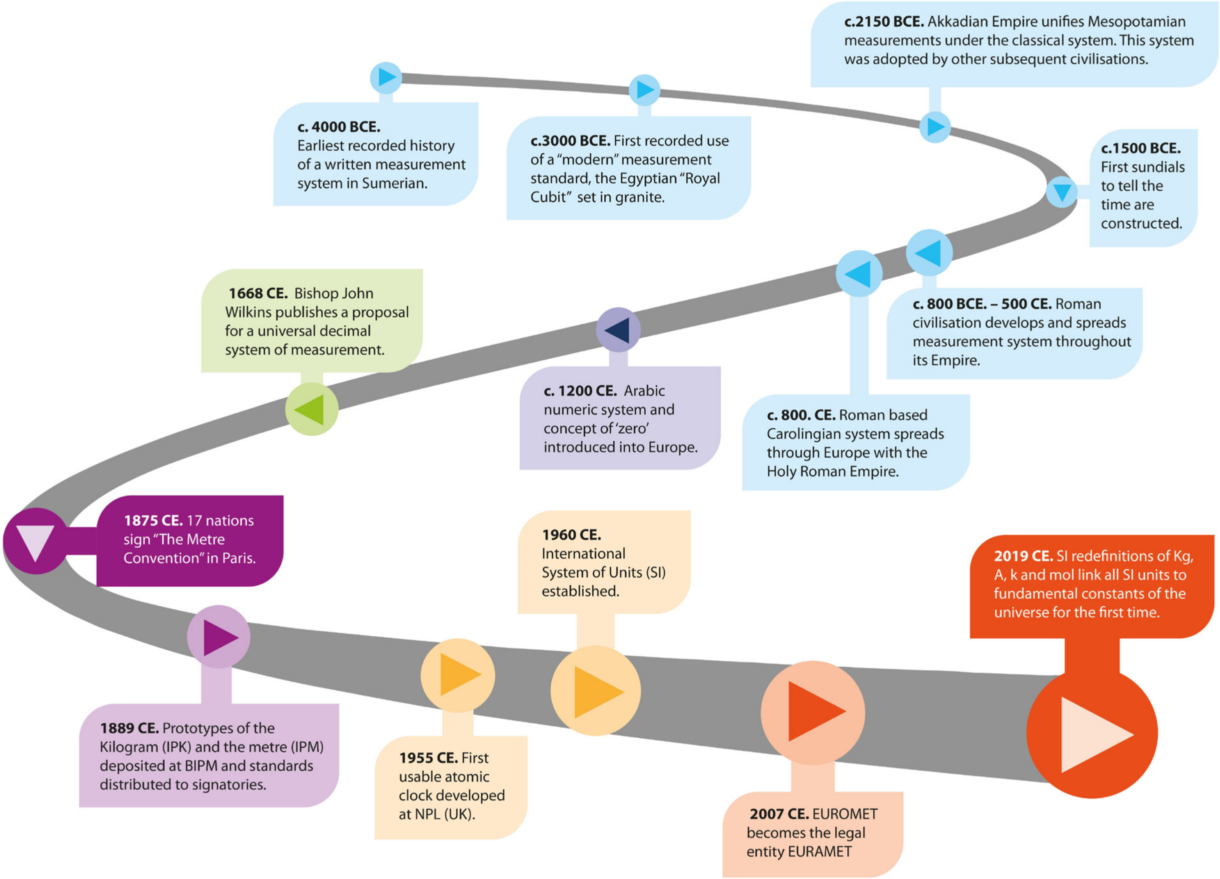
1.2 The history of measurement: How our system has evolved

Every culture is dependent upon trade; therefore, it is no surprise to find that the very first civilisations used measurements to regulate commerce (*Figure 1.1*).

In these early measurement systems units of size were often based on the length or breadth of an arm, palm, hand, finger, foot and so on. Time was measured by the passage of heavenly bodies such as the sun, moon and constellations. Volume was perhaps the most variable measurement, often being based upon bowl or vessel sizes or the amount of a substance held in cupped hands.

Due to its relative uniformity in size, the basic unit of mass was often calculated from a single grain of wheat. In a sense, the seed could be considered to be the first proto-standard as its use arose independently in disparate societies throughout the ancient world.

When cultures were restricted to small groups or communities, there was little need for more than a locally agreed measurement system suitable for regional trade or construction. As societies spread and traded with each other, however, some measurement standardisation was needed. Many measurements became formalised into physical representations, such as rods or chains, with a defined weight or length. In some cases, such as the Royal Egyptian Cubit (circa 3000 B.C.E.) they were quite literally 'set in stone' (see *Figure 1.1*).



c. 4000 BCE. Earliest recorded history of a written measurement system in Sumerian.

c.3000 BCE. First recorded use of a "modern" measurement standard, the Egyptian "Royal Cubit" set in granite.

c.2150 BCE. Akkadian Empire unifies Mesopotamian measurements under the classical system. This system was adopted by other subsequent civilisations.

c.1500 BCE. First sundials to tell the time are constructed.

c. 800 BCE. – 500 CE. Roman civilisation develops and spreads measurement system throughout its Empire.

c. 800. CE. Roman based Carolingian system spreads through Europe with the Holy Roman Empire.

c. 1200 CE. Arabic numeric system and concept of 'zero' introduced into Europe.

1668 CE. Bishop John Wilkins publishes a proposal for a universal decimal system of measurement.

1875 CE. 17 nations sign "The Metre Convention" in Paris.

1889 CE. Prototypes of the Kilogram (IPK) and the metre (IPM) deposited at BIPM and standards distributed to signatories.

1955 CE. First usable atomic clock developed at NPL (UK).

1960 CE. International System of Units (SI) established.

2007 CE. EUROMET becomes the legal entity EURAMET

2019 CE. SI redefinitions of Kg, A, k and mol link all SI units to fundamental constants of the universe for the first time.

Figure 1.1. Historical time-line of key metrological developments.

Time-line from proto-cuneiform tablets (c.4000 B.C.E) detailing 12 measurement systems prevalent in the Sumerian city of Uruk to the international introduction of the SI units redefined in terms of fundamental physical constants (2019 C.E.).

One of the most enduring systems of measurement was that of the Romans (c. 800 B.C.E.–500 C.E.) and several of their units still linger in our terminology to date. Their weight standard, the pound, for example, was derived from a copper bar known as an “as” or “libra”. It is from this the abbreviation in the imperial system “lb” derives.

Around three centuries later, this measurement system was revived and disseminated throughout the western world by the Holy Roman Emperor Charlemagne. Known as the Carolingian system, it remained the basis for European measurements for the next thousand years. By the time of the French Revolution (1789) however, it had become so fragmented that it has been estimated that there were seven or eight hundred different terms for these measurements in use in France alone.

1.3 The birth of the metric system

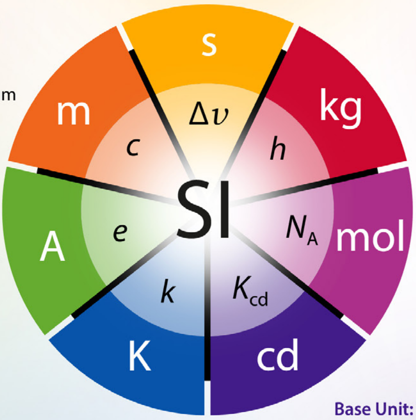
It wasn't until the end of the Renaissance period in the 17th century that the idea of a universal measurement system began to be disseminated by an increasing number of influential theologians, scientists and politicians.

For example, the French abbot Gabriel Mouton, put forward an idea in 1670 for a new unit of length that would influence later developments. He proposed that the unit should be linked to what was considered a physical constant at that time (the Earth's circumference) and that it should be decimally divided. However, it would take a further century before this idea would be realised.

In 1790 Charles-Maurice de Talleyrand, the French minister for foreign affairs, directed the Academy of Sciences to determine the best way to standardise length based on the ideas of Mouton. They decided that the new unit, called the metre, from the Greek word *metron*, meaning “a measure”, be determined as 1/10,000,000th of the distance from the North Pole to the Equator.

Three years later this became a reality with the creation and deposition of two metre standards in the Archives de la République in Paris. From this new measurement of length (the metre) two further units were derived: the kilogram, defined as the weight of water in a cube whose sides are one-tenth of one metre and the litre, defined as the volume of one kilogram of water.

This new system slowly gained acceptance, and, on the 20th May 1875, 17 nations signed the “Metre Convention”. Signatories to this new treaty agreed to promote the metric system, to create standards for the metre and the kilogram and to set up an organisation to maintain the standards and coordinate comparisons (see *Chapter 2*). Another important step was the incorporation of the ‘astronomical second’ in 1889 as the unit of time.



Base Unit: Second
Symbol: s
SI unit: Time
Definition: Defined by taking the fixed numerical value of the caesium frequency $\Delta\upsilon_{Cs}$, 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}.

Base Unit: metre
Symbol: m
SI unit: Length
Definition: 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 $m\ s^{-1}$, where the second is defined in terms of the caesium frequency $\Delta\upsilon_{Cs}$.

Base Unit: kilogram
Symbol: k
SI unit: Mass
Definition: Defined by taking the fixed numerical value of the Planck constant h to be $6.626\ 070\ 15 \times 10^{-34}$ when expressed in the unit J s, which is equal to $kg\ m^2\ s^{-1}$, where the metre and the second are defined in terms of c and $\Delta\upsilon_{Cs}$.

Base Unit: ampere
Symbol: A
SI unit: Electrical current
Definition: Defined by taking the fixed numerical value of the elementary charge e to be $1.602\ 176\ 634 \times 10^{-19}$ when expressed in coulombs, which is equal to A s, where the second is defined in terms of $\Delta\upsilon_{Cs}$.

Base Unit: mole
Symbol: mol
SI unit: Amount of substance
Definition: Defined as one mode containing exactly $6.022\ 140\ 76 \times 10^{23}$ elementary entities. This number is the fixed numerical value of the Avogadro constant, N_A, when expressed in the unit mol^{-1} and is called the Avogadro number.

Base Unit: kelvin
Symbol: K
SI unit: Thermodynamic temperature
Definition: Defined by taking the fixed numerical value of the Boltzmann constant k to be $1.380\ 649 \times 10^{-23}$ when expressed in the unit $J\ K^{-1}$, which is equal to $kg\ m^2 s^{-2}\ K^{-1}$, where the kilogram, metre and second are defined in terms of h, c and $\Delta\upsilon_{Cs}$.

Base Unit: candela
Symbol: cd
SI unit: Luminous intensity in a given direction
Definition: 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, metre and second are defined in terms of h, c and $\Delta\upsilon_{Cs}$.

Figure 1.2. The International System of Units (SI) are all now defined and linked to physical constants.

The seven core units of the SI are now all defined in terms of invariant, fundamental constants. Whilst some of these had been re-defined previously, the majority of the SI units were changed in 2019.

In 1960, at the 11th General Conference on Weights and Measures (CGPM), the International System of Units (Système International d'Unités) or SI, was introduced. Three further units were ratified for use in the system, the ampere (electrical current), the kelvin (thermodynamic temperature) and the candela (luminous intensity). Eleven years later, the mole, the unit for the amount of a substance, was added completing the set of SI base units that are in use today (see *Figure 1.2*).

1.4 New SI definitions for the 21st Century: "for all times, for all people"

On the 16th of November 2018 at the 26th CGPM, the Metre Convention's Member States voted to revise the SI. All seven units would be uniformly expressed using an explicit-constant formulation, with a set of instructions that allow the definitions to be realised in practice at the highest level (*mise en pratique*).

The kilogram, the ampere, the kelvin and the mole were redefined, linking their values to fundamental constants, thus bringing them into line with the other units which had been linked previously.

On May the 20th each year, the signing of the Metre Convention is celebrated as World Metrology Day and on this date in 2019, 144 years after this event, these changes came into effect.

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1.4.1 Rationale for revision

In the 20th Century the early SI standards were initially either based on theoretical constructs or physical artefacts. However, when a physical, primary standard changes, for whatever reason, it generates a paradox within a measurement system. For example, if the physical standard representing a kilogram was damaged and a 10 g piece was broken off, in *reality* this standard no longer weighs a kilogram but is 990 g. However *theoretically* - and within the system - it is still *exactly* one kilogram as this object is the *defining standard*. The same issue applies, but less obviously, if the standard is changed by absorption of contaminants or erosion by cleaning or handling.

Attempts have been made to counter this type of problem and several of the SI units, such as the metre, have undergone a number of revisions.

In 1960, in an effort to replace the physical primary standard for the metre, this unit was redefined in terms of the emission wavelengths of the krypton-86 atom in a vacuum. Over time, however, it became apparent that such a definition was still not ‘sufficiently precise’. One reason for this is that any measurement we make is subject to *uncertainty* (see *Chapter 3*). In the case of the mid-20th century metre definition this uncertainty included environmental factors such as the local refractive index of air and the measurement uncertainty inherent in the interferometers used. When the metre was redefined in 1983 in terms of the speed of light in a vacuum (c) much of this uncertainty was removed and this remains the SI definition to this date (see *section 1.4.2*).

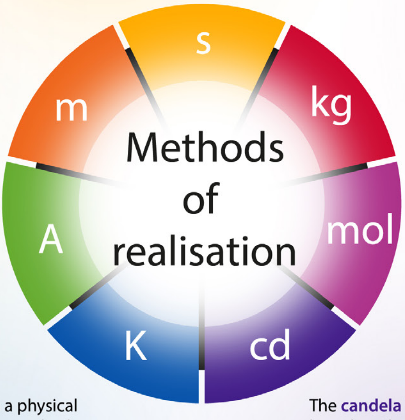
As fundamental constants are invariants of nature then, once experimental realisations or “*mise en practiques*” are linked to them, further SI revision will become redundant. They are, in effect, future proofed.

1.4.2 Realising the revised SI

The definition of the SI units is of little practical value until they are *realised*. The definition is the ‘ideal’ measurement and realisation of this ideal is usually performed by experimentation to derive a value as close to the ideal as scientifically possible. Once this realisation has been made its value can be stored as a representation, which acts as a master or primary standard against which other representations can be compared (see *Chapter 3*).

In the case of the revision of the SI the realisation involved the cumulation of over a century of scientific advancement in measurement. It was very much a collaborative effort by the scientific community involving academic groups, National Measurement Institutes and Designated Institutes under the auspice of Regional Metrology Organisations around the world (see *Chapter 2*).

Redefinitions of the SI units in terms of physical constants began with the base unit of time in 1967 (see *Figure 1.2* and *1.3*). It took almost a further 50 years for scientific measurements to evolve sufficiently to allow measurement uncertainties for all the constants to achieve negligible levels.



The current definition of the **second** was defined in 1967 as the duration of 9 192 631 770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the caesium-133 atom. The second prior to this was the 1956 definition of a fraction of the time of the orbital period of the Earth around the Sun; the ephemeris second. To validate the atomic clock used it was compared to the older ephemeris second, timed with a moon base camera, over a period of 2.75 years.

The **metre** was redefined in 1983 in terms of the speed of light in a vacuum when the estimated uncertainty of the measurements were considered to be sufficient by the CGPM. The redefined metre was realised using result agreement from wavelength measurements based on the radiation of lasers locked on a molecular absorption line in the visible or infrared region.

The **kilogram** is now linked to the Planck constant (*h*) after careful determination using a kibble balance. This instrument balances the force produced by a wire coil carrying current sitting in a magnetic field with a weight of known mass. Removing the mass causes the wire to move and this induces a voltage in the wire. This, in conjunction with quantum-based equations for the Josephson and Hall effects allows the Planck constant to be measured in terms of mass, length and time.

To determine **ampere**, the value of the elementary electrical charge, e, nanometre sized quantum electronic devices termed single-electron pumps (SEPs) had to be constructed. Operating at temperatures approaching absolute zero they are capable of emitting single electrons with higher accuracy and stability than anything previously available.

The **mole** is now linked to Avogadro's constant (N_A) and this was realised by counting the number of individual atoms in incredibly precise, silicon-28 enriched spheres and measuring their volumes using interferometry (the counting method).

Prior to 2019 the **kelvin** was based upon a physical property (the triple point of water). Three methods were examined Johnson Noise thermometry (JNT), Acoustic gas thermometry (AGT) and Dielectric-constant gas thermometry (DCGT). It is now linked to the Boltzmann constant (*k*) using Dielectric-constant gas thermometry. This method consisted of determining the changes in the capacitance of a capacitor containing a dielectric gas (helium); to do this a gas purity of better than 99.99999 % had to be achieved.

The **candela** is the unit of luminous intensity and is based on the human visual system. It was first defined in 1924 and termed the spectral luminous efficiency V(λ). V(λ) is defined in the wavelength domain from 360 nm to 830 nm and normalised to unity at its peak of 555 nm, which is the wavelength that the human eye can best detect. It has gone through several iterations but still matches the original V(λ) but is now realised using a detector-based method directly traceable to a Reference Cryogenic Radiometer and is maintained on a set of well-characterized filter detectors.

Figure 1.3 Methods of realisation of the SI base units.

The SI definition of each base unit represents the "ideal" measurement value for each unit and *realisation* of this ideal is usually performed by experimentation to derive a value as close to the ideal as scientifically possible. As our scientific and technical knowledge has advanced the methods that have been used to realise the units have also advanced. Currently, all SI units are linked to fundamental physical constants.

1.4.3 Benefits of the revised SI

The fundamental constants that all the base units of the SI are now linked to are sufficiently well known so this redefinition does not significantly affect current measurements. However, one advantage to this change was that it imparted a longevity in the system. Future innovation in measurement techniques could reduce uncertainties in these values even further to give practical benefits without requiring another redefinition of the units.

Indeed, for most of us, the precise realisation of the SI base units will remain abstract constructions until they are available in the real world. In time however, they will filter down to all of us through the co-ordinated activities of the thousands of scientists and individuals of the National Measurement Institutes around the world (see *Chapter 2*).

1.4.4 Derived units, Notation, Symbols and units based on the SI (and beyond)

The 7 base units of the SI, the kilogram, metre, ampere, kelvin, second, candela and the mole (see *Figure 1.2*) can be used to derive further units of measurement (*Appendix 1*, *Table A1.1*). They can also be expressed in terms of decimal multiples and submultiples and these measurement quantities gain a prefix e.g., 1000 metres (1 x 10^3 metres) is given the prefix **kilo**metre (*Appendix 1*, *Table A1.2*). In a number of cases SI units do not have a dimension, for example when the output of a measurement is a ratio or a count such as refractive index, these are termed dimensionless units (see *Appendix 1*). There are also units that are not derived from the base units of measurement, but which are recognised by the SI (as they are often of historical or traditional significance such as the hectare or the hour). In all these cases, to avoid confusion, specific rules are given as to their use and nomenclature (*Appendix 1*, *Table A1.4*). For further information see the SI brochure available on the BIPM webpage: https://www.bipm.org/en/publications/si-brochure.

Chapter 2. The worldwide measurement system

Chapter 2. The worldwide measurement system

Introduction

At the core of our 21st century metrological infrastructure is a 19th century treaty, the Metre Convention, and the organisation that was created to implement it. This almost unprecedented international agreement ushered in the use of the metric system which later evolved into the International System of Units (the SI, see *Chapter 1*) that we use today.

To ensure that any measurements we make can be *accepted and trusted* at a national or international level, however, requires two things; that the measurement can be traced back to the primary standard from which it was realised, in a traceability chain (see *Chapter 3*) and that it is also in agreement with similar measurements made elsewhere. We now have systems in place, comprising many organisations that co-operate across the globe, that allow us to address these issues.

2.1 The development of international metrology

As the 19th century progressed the world began to shrink with the development of the railways and telegraph systems. Nations that were previously geographically separate could now interact with unprecedented ease. However, these advances also brought new problems such as the disparity in the measurements each nation used which was highlighted at the first of the Great Exhibitions held in London in 1851.

Although primarily a platform for the various nations to display their industrial and technological advances the Great Exhibitions also served as a forum for scientists and engineers to voice common goals. It was at the end of the exhibition held in Paris in 1855 that a formal call was made for the establishment of a worldwide system of weights and measures based on the decimal metric system. Twelve years later, at the second Paris exhibition (1867), the Committee for Weights and Measures and Money was formed. In the same year the International Conference of Geodesy, held in Berlin, recommended the international use of the metric system, the construction of a new European prototype of the metre and the creation of an international commission.

These calls led to the signing of an international diplomatic treaty in 1875 - the Metre Convention. This treaty is still in force and 64 Member States, and 36 Associate States and Economies were members in 2023 – covering over 95 % of the world economies.

The original convention ratified the use of the decimalised metric system and the BIPM, which it established, remains central to the metrological infrastructure to this day (see section 2.2).

2.1.1 The development of the National Measurement Institutes (NMI)

The signing of the Metre Convention and the subsequent ratification of the metric system as an international basis of measurements brought an increase in both trade and technology to the signatory nations. It also raised new problems however - the chief one of which was how the new system would be regulated and adhered to.

In response to this, dedicated institutions began to form, initially in the most industrialised nations. The first NMI was established in Berlin in 1887 as the Physikalisch-Technische Reichsanstalt (PTR) and this was followed by the establishment of others such as the National Physical Laboratory (NPL) in the UK in 1900, the Laboratoire National De Metrologie et D'Essais (LNE) in France and the National Bureau of Standards (NBS) in the USA in 1901.

The original purposes of these institutes were in a similar vein. NPL, for example, was founded with the aim of "*standardising and verifying instruments, for testing materials, and for the determination of physical constants*." Although the remit of NMIs have been extended over the years, as the need for metrological services has increased, these principles remain at the core of the NMIs to this day (see *section 2.2*).

2.1.2 The development of the Regional Metrological Organisations and EURAMET

As the 20th century progressed almost all industrial countries had established, or had begun to establish, their NMIs and many of these began collaborative initiatives to improve metrology in general. It was around the seeds of these initial relationships that the Regional Metrological Organisations (RMOs) began to form, mainly along the lines of geographical, economic or political affinities.

The first RMO to be established was in the Asia-Pacific region (1977) in response to a UK Commonwealth Science Council initiative. Its initial members were countries from inside the Commonwealth but in 1980 external countries joined and this became the Asia Pacific Metrology Programme (APMP, see *Figure 2.1*).

The genesis of the first RMO in Europe can be traced back to the formation of the Western European Metrology Club (WEMC) in 1974 which led to creation of the European Collaboration on Measurement Standards (EUROMET) in 1987 based on a memorandum of understanding (MoU).

One of the main drivers for the establishment of EUROMET was shared by the other RMOs; by co-ordinating the activities of the member countries it could "*improve the promotion of metrological services and activities through an increase in the efficiency of resource use*". In other words, time and resources would not be wasted by unnecessary duplication of work or research in differing countries.

12 years after the formation of EUROMET another key milestone in modern metrology occurred – the inception of the CIPM Mutual Recognition Arrangement (CIPM MRA, see *section 2.3*). This arrangement not only reinforced the confidence in the measurement data produced by the NMIs, but it also acted as a framework for further work. In response to this and the growing metrological needs of the international communities, the European Union launched a number of studies and research programmes:

- MERA (Metrology for European Research Area, 2002 - 2003)
- iMERA (implementation of MERA, 2005 - 2008)
- iMERA PLUS (2007 - 2012)
- EMRP (European Metrology Research Programme, 2009 - 2013)
- EMPIR (European Metrology Programme for Innovation and Research, 2014 - 2020)
- European Partnership on Metrology (2021 - 2027)

These programmes, in particular MERA and iMERA, which EUROMET led, fostered greater inter-European co-operation that resulted in its evolution to the present European RMO, the European Association of National Metrology Institutes (EURAMET) in 2007.

Figure 2.1. Geographical location of the Regional Metrological Organisations (RMOs).

There are currently six Regional Metrological Organisations (RMOs) that are recognised. The *Inter-American Metrology System* or SIM spans the North and South Americas. The *European Association of National Metrology Institutes* (EURAMET) covers the European area and the *Intra-Africa Metrology System* (AFRIMETS) covers most of the African continent. The *Euro-Asian Cooperation of National Metrology Institutions* (COOMET) spans those parts of Eurasia not covered by EURAMET and the oldest RMO, the *Asia Pacific Metrology Programme* or APMP covers parts of Oceania as well as India, Japan, Pakistan, and China. The youngest, and smallest, RMO is the *Gulf Association for Metrology* (GULFMET) which, as of 2019, covered areas in the middle east. *Image: courtesy of BIPM.*

2.2 Current metrological infrastructure

The foundation of the current infrastructure of the world's metrology was laid down with the signing of the Metre Convention in 1875 (see *Chapter 1* and *Figure 2.2*).

At the top level is the General Conference on Weights and Measures (CGPM) which comprises delegates drawn from Member States and observers from Associates of the CGPM. It acts as a forum for its members to:

- Decide what is required to ensure the improvement and propagation of the International System of Units (SI).
- Endorse the results of new fundamental metrological determinations of scientific resolutions, such as the addition of SI base units or any required SI revisions.

The CGPM also elects up to 18 representatives from different nations to form the International Committee for Weights and Measures (CIPM).

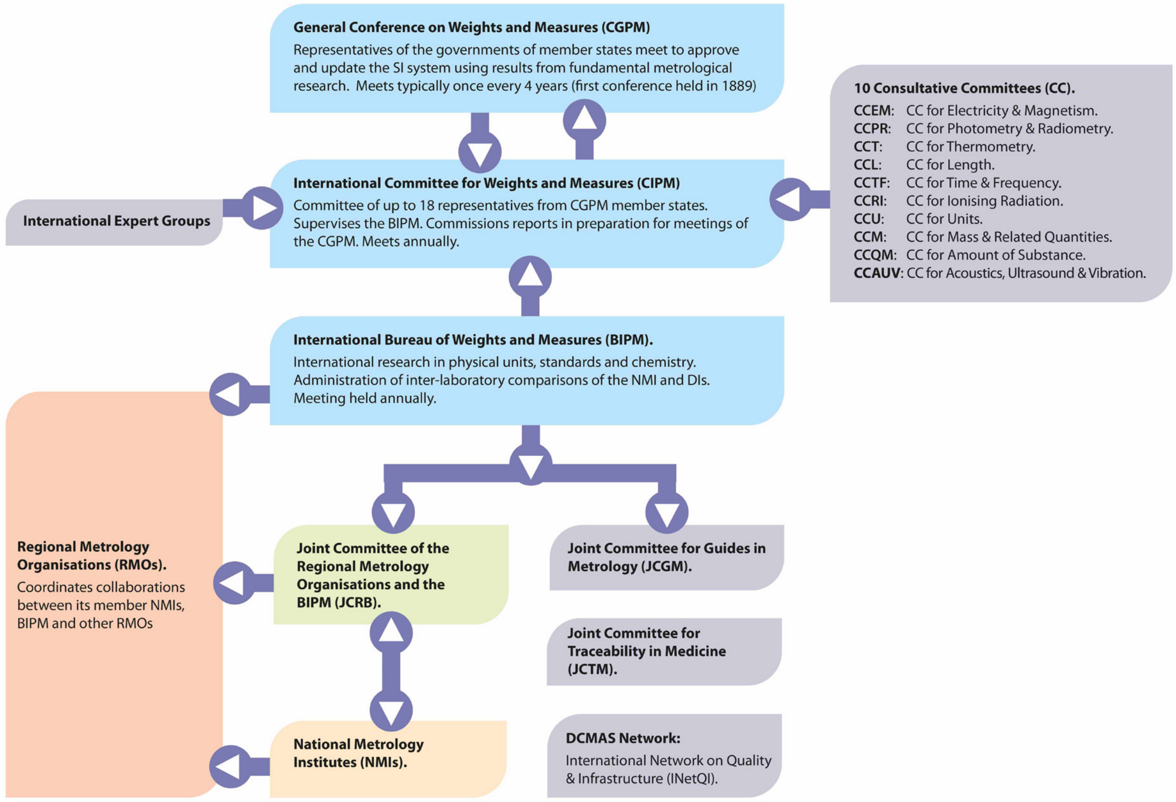


Figure 2.2. Core metrological institutions of the Metre Convention.

Signatory members of the metre treaty meet every 4 years at the General Conference on Weights and Measures (CGPM) which, amongst other things, endorses the results of new fundamental metrological determinations of scientific resolutions, such as the addition of SI base units or any required SI revisions. It also elects up to 18 representatives from CGPM member states to form the International Committee for Weights and Measures (CIPM). The CIPM reports to the CGPM, and it promotes international uniformity in units of measurement and directs the International Bureau of Weights and Measures (BIPM) which establishes and maintains the reference standards used as a basis for international comparisons at the highest level. Supporting these core institutions are a large number of consultative or joint committees as well as national and regional metrology organisations and international expert groups. The arrows indicate organisational interactions.

The CIPM is delegated by the CGPM, to which it reports, to promote international uniformity in units of measurement. This can involve proposing resolutions to the CGPM but more importantly it directs the activities of the International Bureau of Weights and Measures (BIPM), based in Sèvres, France, and 10 consultative committees (CCs).

The CCs, each covering a particular aspect of metrology, are composed of representatives of the NMIs and other experts. They advise the CIPM on scientific matters influencing metrology within their technical area, including any BIPM scientific programme activities.

The CIPM has a number of other roles:

- To establish global compatibility of measurements through promoting traceability to the SI.
- Where traceability to the SI is not yet feasible, to link measurements to other internationally agreed references such as hardness scales and reference standards established by the World Health Organization (WHO).
- Contributes to the implementation and maintenance of the CIPM MRA (see *section 2.3*).
- To act as a forum for the exchange of information about the activities of the CC members and observers.
- Create opportunities for collaboration.

Working with the NMIs, through the CCs, the BIPM establishes and maintains the reference standards used as a basis for international comparisons at the highest level. In some cases, this is done directly through the provision of selected comparisons under the BIPM's technical programme. This originated from its inception in the 19th century when the BIPM was the repository of the first international kilogram and metre standard (see *Chapter 1*), and these artefacts still reside with them today. In other cases, the BIPM facilitates the traceability of measurements to comparisons carried out by the NMIs and RMOs.

The BIPM is the main body for liaison between the metrological community, inter-governmental organisations and other international bodies. To perform these tasks, the BIPM relies upon the input from the RMOs and NMIs as well as a number of joint committees (see *Figure 2.2*).

2.2.1 The Regional Metrology Organisations (RMOs)

The collaboration of NMIs at a regional level is coordinated by the continent-spanning Regional Metrology Organisations (RMOs, see *Figure 2.1*) and currently 6 RMOs are recognised (see *section 2.3*). Depending upon location and the composition of their member states, each RMO has a different organisation and internal structure. For example, some RMOs have organisations dealing with matters of legal metrology (see *Chapter 4*) whilst others do not.

However, as they all formed in response to similar needs and goals, they all share certain features. The example of the European RMO is given below.

2.2.2 The European Association of National Metrology Institutes (EURAMET)

EURAMET was formed in Berlin on 11th January 2007 with the signing of the EURAMET constitution by its 22 founding members. By 2024 the number of full members had grown to 38. EURAMET has a number of roles, which are also shared by other RMOs, and includes:

- Co-ordination of Metrological activities; such as interlaboratory comparisons of national measurement standards, scientific knowledge and experience transfer and the calibration and measurement capabilities (CMCs, see *section 2.3*) of its members.
- Co-operation in metrology research and development; in developing the metrological infrastructure of the member countries and technical co-operation with RMOs and metrology institutes outside of the RMO.
- Dissemination of metrological knowledge; by joint training and consultation, sharing of technical capabilities and facilities and facilitating traceability to primary realisations of the SI.

2.2.3 The European Metrology Networks (EMNs)

In 2018 EURAMET launched its European Metrology Networks (EMNs) in areas considered to be of vital importance to Europe. These networks cover fields such as Advanced Manufacturing, Energy Gases, Laboratory Medicine, Climate and Ocean Observation, Smart Electricity Grids and Pollution Monitoring. In these areas the EMNs act as a single point of contact for metrology in their specified areas.

By providing a single point of contact for information, underpinning regulation and standardisation, promoting best practice and establishing a comprehensive, longer-term infrastructure, the EMNs aim to create and disseminate knowledge, gain international leadership and recognition, and build collaboration across the measurement science community.

2.2.4 National Metrology Institutes and Designated Institutes (NMI and DI)

National Metrology Institutes (NMIs) are designated by the nation in which they reside, and they represent that country internationally in relation to external agencies such as other NMIs, RMOs or the BIPM.

The realisation of the SI is one of the core functions of the NMIs along with maintaining the representations of these units for comparison (see *Chapter 1*). Not every NMI will have the capability to perform experiments at the level required to realise the SI base units in terms of the physical constants. This means that most will realise these or other measurements using secondary standards which are traceable to other NMIs. Indeed, this inter-NMI collaboration is one of the main roles of the RMOs. As well as the development of new and improved measurement standards, the NMIs generate measurement methods for dissemination and, in many cases, reference materials to enable others to establish traceability to the SI (see *Chapter 3*).

NMIs perform another crucial function in that they instil *trust* in the measurements that are made. One way this is demonstrated is through measurement comparison studies. These are generally Key Comparisons (KCs) proposed by the Consultative Committees and performed under the umbrella of the CIPM Mutual Recognition Arrangement (CIPM MRA, see *section 2.3*) although on occasions they can also be Supplementary Comparisons (SCs). SCs are carried out by an RMO to meet specific needs not covered by Key Comparisons, such as regional needs or measurements of parameters not within the 'normal' scope of the Consultative Committees and these are generally proposed by the RMOs' Technical Committees (TCs). The national government or, if it has been delegated the role, the NMI may appoint other institutes to hold specific national standards, and these are referred to as Designated Institutes (DIs). Many DIs also participate in the CIPM MRA activities (see *section 2.3*).

Some countries operate a centralised metrology organisation with one NMI, other countries operate a decentralised organisation with a lead NMI and a multiplicity of designated institutes. As the importance of metrology in non-traditional areas such as biology, chemistry, medicine and food increase the latter structure is gaining traction as few countries have an NMI that covers all these subject fields.

2.3 The CIPM Mutual Recognition Arrangement (CIPM MRA)

The method that the NMIs use to demonstrate the international equivalence of their measurement standards, and the calibration and measurement certificates they issue, is through the CIPM Mutual Recognition Arrangement (CIPM MRA).

The CIPM MRA came about as a response to resolution 2 of the 20th CGPM and was first signed in 1999. By 2024 there were 250 institutes participating in the CIPM MRA, comprising 97 NMIs, 4 international organisations and 149 designated institutes, covering around 90 % of world trade in merchandise exports.

The CIPM MRA comprises two parts. The first part relates to the establishment of the degree of equivalence of national measurement standards, in other words in establishing how similar or dissimilar a particular measurement result, technique or procedure is between different institutions or different nations. This is generally determined by the performance of interlaboratory comparison studies.

For example, several NMIs, often in conjunction with a CIPM Consultative Committee, may engage in generating a value for a specific measurand. These values are then compared with each other to generate a range of values from which the uncertainty value for these measurements can be determined. This process not only generates knowledge about a NMI's measurement capability but also allows the international validity of these measurements to be recognised.

The second part of the CIPM MRA concerns the *mutual recognition* of calibration and measurement certificates issued by participating institutes. Thus, the CIPM MRA also serves as a framework for the mutual acceptance of the results from each NMI.

2.3.1 CIPM MRA structure and outputs

- Only one NMI per Member State can sign the CIPM MRA.
- Other institutes that hold recognised national standards in that country may also be designated and participate in the CIPM MRA through the signatory NMI and are generally referred to as Designated Institutes (DIs).
- An NMI can choose to join only part one or both parts of the CIPM MRA.
- NMIs of Associate States of the Metre Convention can participate in the CIPM MRA only through a Regional Metrology Organisation.
- International and intergovernmental organisations designated by the CIPM may also join the CIPM MRA.

The participation of an NMI or DI in the agreement gives international credibility and acceptance of the measurements it makes. This assurance also extends to the various accredited calibration laboratories that can demonstrate the traceability of their measurements to a participating NMI or DI.

The outcomes of the CIPM MRA are statements of the Calibration and Measurement Capabilities (CMCs) of each NMI or DI. These results are designed to be open and transparent and are the published results of comparison studies maintained in the publicly available BIPM Key comparison database (KCDB) available from its website (https://www.bipm.org/kcdb/). The Joint Committee of the Regional Metrology Organisations and the BIPM (JCRB) is responsible for analysing and approving entries into the KCDB database.

2.3.2 BIPM Key comparison database (KCDB)

The KCDB consists of four parts, which are considered appendices to the CIPM MRA:
- **Appendix A**: *List of participating NMIs and Designated Institutes (DIs).* As of July 2024, the CIPM MRA had been signed by the representatives of 250 institutes, 4 international organisations and 149 designated institutes.
- **Appendix B**: *Results of key and supplementary comparisons.*
- **Appendix C**: *Calibration and Measurement Capabilities (CMCs) of the NMIs and Designated Institutes.*

As of July 2024, the number of registered CMCs was 25917, all of which had undergone a process of peer evaluation by NMI experts under the supervision of the Regional Metrology Organisations and coordinated internationally by the JCRB.

- **Appendix D**: *List of key comparisons*. As of July 2024, 1179 key and 694 supplementary comparisons were registered in the database.

2.3.3 Accredited Laboratories

Measurement comparison studies can give international confidence in the ability of the measurement process or the NMI performing it. However, there also exists a mechanism that allows international confidence and recognition of results from more regional laboratories and this is laboratory accreditation (see *Chapter 3*).

Chapter 3. Harmonised measurement standards and traceability

Chapter 3. Harmonised measurement standards and traceability

Introduction

An essential part of any metrological process is the use of standards. Without them it would be difficult, if not impossible, to compare the values of any measurements made and their importance is highlighted by their existence in our culture since the dawn of writing (see *Chapter 1*).

Our reliance on standards continues to the present day and much of our daily lives are influenced by them. Trade, for example, is often considered to involve giant corporations but it also encompasses every purchase an individual makes from tickets for the lottery draw to the latest tablet or phone.

When we buy a lottery ticket, we can be sure that gravity, bounce and chance are the only factors that affect the drawing of a certain ball. This is because each of these balls has been painstakingly checked to ensure that their weight, diameter, sphericity, surface texture, and so on, are all within specified tolerances with one another. This is done using a suite of high precision measurement instruments – all requiring calibration to a particular measurement standard.

In the same way, each of the individual components of an electrical product, from the capacitors, transducers, LEDs, to the surge protectors, have all been manufactured and checked against an international standard for that component.

3.1 Measurement standards and traceability to the SI

In a metrological context there are, broadly speaking, two types of standards: measurement standards and documentary or technical standards.

Measurement standards, also known as *etalons*, are a physical quantity with a defined or known value and an associated measurement uncertainty against which the item to be measured, the measurand, is compared. This type of standard can be a physical artefact, such as the metre prototype in the 'old SI' scheme or a stored measurement value, such as the speed of light for determining the metre in the 'revised SI' (see *section 1.4*). Regardless of the type of measurement, modern measurement standards must all link back to the SI units in a traceability chain (see *section 3.1.1*).

Technical standards, or documentary standards, on the other hand generally describe specifications, operations or processes that must be performed in order to achieve a particular quality goal. These include such things as the OIML Recommendations for legal metrology (see Chapter 4) or the outputs of many of the organisations involved in standards (see *section 3.4*). Technical standards also relate to areas outside of metrology such as food safety management (ISO 22000) or even customer satisfaction (ISO 10004).

However, it should be noted that a degree of overlap exists between the two types of standards – whilst making and comparing measurements requires standardised methods, about 60 % of documentary standards make reference to measurements.

Regardless of their specific area of coverage all standards are designed to aid the harmonisation of procedures by providing a common language and framework through which these:

- Allow technology to function seamlessly and establish trust so that markets can operate smoothly and with fairness.
- Allow components made by different companies to be interchangeable and compatible.
- Protect consumers by ensuring product safety and performance.
- Speed the introduction of innovative products to the market.

3.2 The Hierarchy of standards and the measurement traceability chain

The SI unit of length, the metre, is now represented by the realisation of the speed of light in a vacuum and the second is now realised by measuring the periods of radiation emitted by caesium atoms (see *Chapter 1, Figure 1.3*). It is clearly impracticable that such methods would be used in a textile factory for checking the length of a roll of cloth, or in a factory making bedside clocks. Not only would it be unrealistic to expect that every manufacturing facility have such systems in place, but there is also no need for such accuracy or precision in the production of these items. However, to ensure that all measurements are consistent across the globe, robust links to the SI are required. For this reason, many types of standards exist for any related measurement and a 'trade-off' is made between a standard's accuracy and its usefulness. This is generally termed the Hierarchy of standards (*Figure 3.1*).

At the top level are the international standards of the SI, with values realised at the highest level of accuracy and stored as representations in a handful of dedicated laboratories around the world. Because of their nature their value is not referenced to any higher standard, and they are often termed the primary metrological standards or primary standards.

Below the international standard are the national standards. These are derived by comparison to the international standards and, although having a lower accuracy than the international standards, still have a measurement value with a low uncertainty. Only one institute per country will hold a national standard for a particular SI unit and these are commonly the National Metrology Institutes (NMIs, see *Chapter 2*). In some cases, the international standard will also be the national standard – such as when an NMI is involved in the realisation of a base SI unit.

From the national standards the reference or calibration standards are generated. These differ from the national standards in that multiple copies tend to exist within a country. Their value must be as close to the national standard as is realistically possible and to ensure consistency they are regularly checked against it. These standards are generally maintained by the calibration laboratories that issue measurement certificates as part of accreditation schemes (see *section 3.2.2*).

At the lowest level are the routinely used working standards. Large numbers of these may be generated for distribution around a country and these include such things as the weights used for the calibration of routinely used balances.

These standards are generally held in locations of a manufacturer who makes or uses measuring devices or by a user to confirm measurement accuracy for routine quality assurance purposes. Periodically they will be sent to a calibration laboratory for certification against a reference standard for confirmation of their stability over time.

There are other classes of standards in routine use, such as travelling standards or measurement devices and reference materials (see *section 3.3*). Travelling standards, are portable measurement standards used as an intermediary device when comparing standards held at different locations in order to create or maintain measurement traceability. The international standard for the ampere, for example, is now derived through the realisation of the elementary electrical charge, e, using quantum electronic devices termed single-electron pumps (SEPs, see *Chapter 1*, *Figure 1.3*). This value can be transferred to national laboratories by calibration of their standards with the BIPM transportable Josephson and quantum-Hall system.

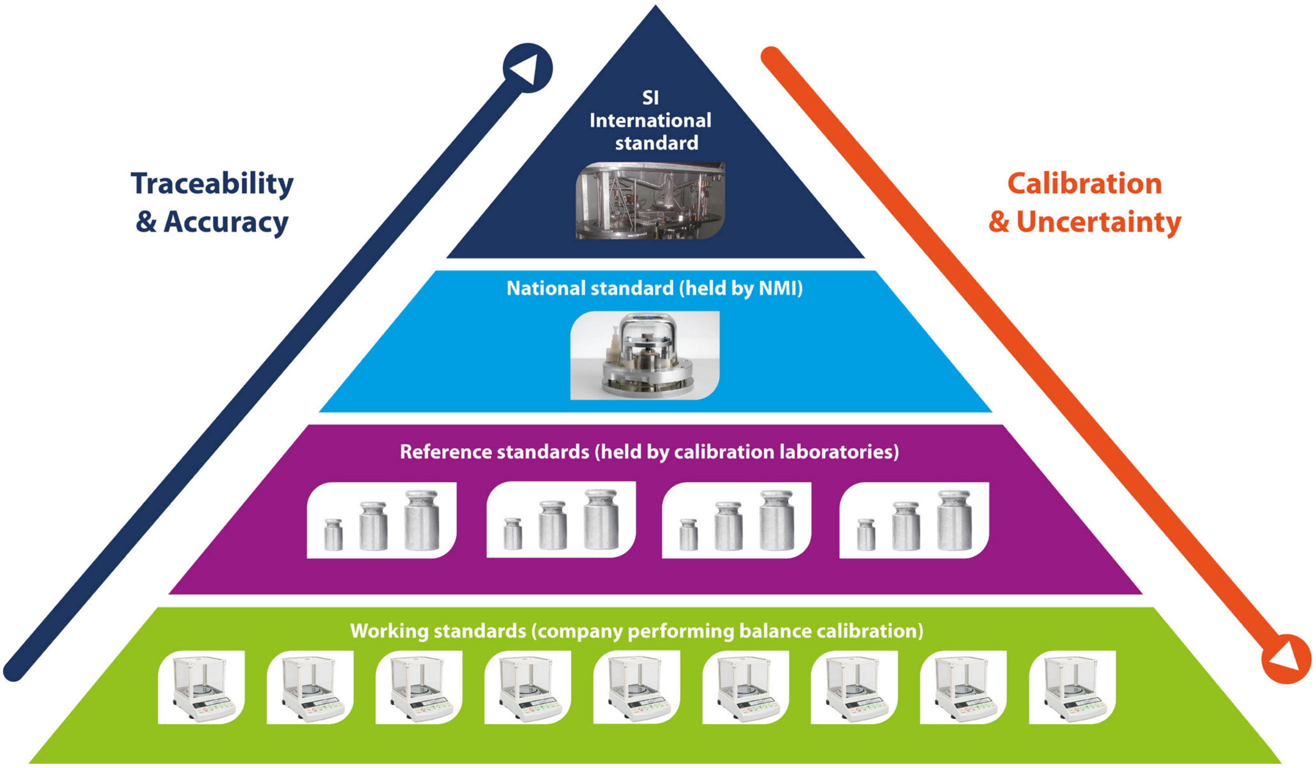


Figure 3.1. Traceability and uncertainty in the Hierarchy of standards.

Different levels of standards exist in terms of their accuracy and utility, and this is termed the Hierarchy of standards. At the top level are the international standards and below these sit the national standard for that unit. From the national standards the reference or calibration standards are generated. At the lowest level are the routinely used working standards. As standards descend the hierarchy the uncertainty in their measurement value increases (red arrow). If the calibration and measurement uncertainty steps are documented throughout, then any measurement made – such as laboratory balance calibration with working standards – can be traced directly back to the SI unit from which it derives in a traceability chain (blue arrow).

3.2.1 Measurement uncertainty in the Hierarchy of standards

Without the generation of the Hierarchy of standards the representations of the SI units would remain as abstract concepts without any real-world links. However, whenever a measurement is made then a degree of uncertainty will be contained within the result. The uncertainty can arise from the measuring device, the environment, or the operator. Whilst the base units of the SI have been realised using the highest level of scientific knowledge, with commensurately small uncertainties, the lower-level standards are generated using less sophisticated techniques and thus have a lower measurement accuracy and a higher measurement uncertainty.

Thus, a calibration standard, created from a national standard, will be less accurate and have a higher uncertainty value than its 'parent' standard. Working standards made from a calibration standard will also be lower in accuracy and higher in uncertainty than that standard – with the added disadvantage in that they also 'inherit' the uncertainty present in the calibration standard in an additive or cumulative manner.

However, provided the uncertainty for each step of this process is calculated and documented in an ***unbroken chain of comparisons*** with each link carrying a calibration certificate, then a measurement traceability chain can be established. This not only allows us to know the overall accuracy of the measurements made using a working standard, for example, but also allows any measurement made to be traced back up to the SI unit or units from which its value was derived.

3.2.2 Ensuring confidence in the traceability chain

The factors that allow confidence in the traceability chain are the accuracy of the standards used, the estimated uncertainty present in their value, and the proficiency of the calibration process performed at each link to certify that the subsequent standard is within a defined value and uncertainty. To ensure that we can have confidence that these have been performed to the same high level of measurement quality throughout the world, a series of checks and evaluations exist, such as accreditation.

As mentioned previously national measurement standards are generally held by the NMIs and DIs within a country and one way that their measurement abilities are assessed is through the CIPM MRA (see *section 2.3*). This provides a structure based on key comparison exercises that ensures that the measurement standards of participating NMIs are equivalent.

Calibration laboratories are responsible for maintaining reference standards and frequently provide the link between both the laboratory holding the national standard and the organisations holding the working standards. These laboratories follow technical standards in their operation such as ISO/IEC 17025. To ensure that they are competent to perform this role they are themselves assessed through a process called laboratory accreditation. Accreditation is achieved through a process of evaluation and regular surveillance by accreditation bodies. These bodies follow technical standards themselves when issuing accreditation certificates such as the ISO/IEC 17011.

Accreditation bodies are generally members of other organisations that aid in their operations. At the international level the *International Laboratory Accreditation Co-operation* (ILAC) ensures that all its members follow the same high standards in laboratory accreditation and there is a mutual recognition arrangement (MRA) in place for members. Signatories to the ILAC MRA agree to accept another laboratory's accreditation as equivalent to their own.

A second international body, the *International Accreditation Forum* (IAF) also has a mutual recognition arrangement (IAF MLA) in place for its members and these two organisations have been working closely together since 2001 to harmonise their activities. The links between accreditation bodies also extend to the regional levels and in Europe the *European co-operation for Accreditation* (EA) develops and maintains the EA multilateral agreement of mutual recognition (EA MLA) which is similar to the ILAC MRA in that it seeks to harmonise accreditation infrastructure. Furthermore, each country will have its own national accreditation bodies which help translate the work of the regional and international bodies and help to co-ordinate accreditation.

The result of all of this is to provide links between each separate accreditation body and consequently, in parallel to the traceability chain, there also exists a 'credibility chain' that allows confidence in the equivalence of any product or measurement made anywhere in the world (see *Figure 3.2*).

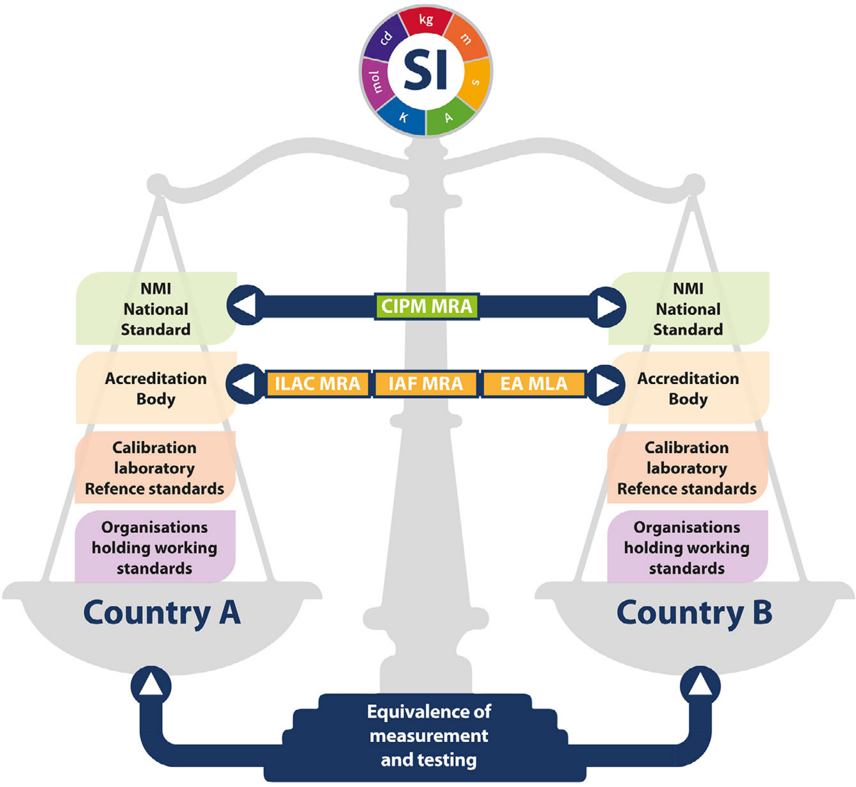


Figure 3.2. Interlaboratory comparisons and accreditation allow the international equivalence of measurements.

To ensure that we have confidence in the equivalence of measurements made in different locations requires a number of assessments. The ability of the NMIs that hold the national standards can be ascertained by interlaboratory comparisons with the NMIs of other nations through the **CIPM MRA**. The competence of calibration laboratories to hold and maintain the reference standards is assessed through laboratory accreditation performed by accreditation bodies. These bodies ensure equivalence with each other through the **mutual recognition** or **multilateral agreements** (**MRA**, **MLA**). When each step has been performed correctly then we can be confident in the measurements or products made by any nation, anywhere in the world.

3.3 Standard reference materials

Often the parameters requiring measurement or calibration are complex, such as a trace element present in a soil sample or the amount of a contaminant in a water source. When this is the case reference materials (RMs) are used. These are usually artificially generated materials which are similar in chemical or biological composition to real samples but in which the analyte of interest has been accurately determined.
The term 'reference material' is generic and can cover a wide range of standards from pure chemical substances to reference objects or artefacts used to assess functional properties, like odour or hardness. They can also be used to measure a quantity of a substance, such as the amounts of dioxin in fish tissue, or to determine an object's nominal value by, for example, the use of colour charts. Reference materials themselves can be characterised by identity, based on their chemical or biological structures, or by a property value, for example the specific amount of a chemical they contain.

In general, there are two classes of reference materials that are recognised by the International Organization for Standardization (ISO), and these are reference materials (RMs) and certified reference materials (CRMs).

RMs must be sufficiently homogeneous and stable with respect to one or more specified properties to be fit for an intended use, such as the assessment of a measurement method or for material value assignment. It is important to note that a RM which is suitable for validating a specific method, for example, may not be suitable for quality control.

CRMs, on the other hand, are characterised by a valid metrological procedure and are accompanied by a certificate that states the value of a specified property, its associated uncertainty, and a statement of metrological traceability.

Often in chemistry and biology complex mixtures, or indeed living systems, are involved. In these, determining the amount of the measurand present can be challenging. Isolating small amounts of a substance we wish to measure from these mixtures may be impossible and clean-up steps could also lose or reduce the amount of target present. In these cases, a matrix reference material or an assay is often used.

Matrix materials are reference materials that are characteristic of a real sample and are intended to be used in conjunction with the analysis of the real samples present in the same, or a similar, matrix. They can be obtained directly from biological, environmental or industrial sources or generated by spiking the component(s) of interest into an existing material. For example, a known amount of a toxin could be added to soil that has no toxin previously to generate a matrix RM and then analytical procedures could be performed on an unknown soil sample and the results compared to the RM.

Assays are often used in biology to measure such things as the amounts of a hormone, drug, or growth factor in blood. To do this a standard curve composed of known quantities or concentrations of the target is generated and the unknown quantity is compared against this to determine its concentration.

Many outstanding problems exist for some measurements involving RMs and dedicated metrology groups, such as ISO/TC 334 (the Technical Committee on Reference Materials of the International Organization for Standardization) and the JCTLM (the Joint Committee for Traceability in Laboratory Medicine) are working to address these problems.

3.4 International and European Institutes involved in standardisation, accreditation and calibration

There exists a large number of international, regional and national organisations which between them generate, maintain or co-ordinate the implementation of tens of thousands of standards, mostly of a documentary or technical nature. The documentary standards fall into two general categories, Normative and Informative. Normative documents are those that contain requirements which must be met in order for claims of compliance (see *Chapter 4*) with the standard to be certified. European "EN" standards, for example, fall into this category. Informative documents, however, do not contain any requirements and it is therefore not possible for compliance claims to be certified.

Europe has three main standards institutes that produce technical and measurement standards. These are CENELEC, ETSI and CEN and collectively they form what is known as the European Standards Organisations (ESOs).

The ESOs are:

- The *European Committee for Electrotechnical Standardization* (CENELEC) founded in 1973, produces standards in the electrotechnical engineering field.
- The *European Telecommunications Standards Institute* (ETSI) founded in 1988, supports standards for information and communications technology (ICT) enabled systems, applications and services.
- The *European Committee for Standardization* (CEN) founded in 1961, aims to improve the economy and the welfare of European Union (EU) citizens through development, maintenance and distribution of standards and specifications covering a wide range from air and space to healthcare and the environment.

The ESOs are recognised in the EU as being competent in the area of voluntary technical standardisation as per EU Regulation 1025/2012. The European Standards (EN) that they produce carry with them the "obligation to be implemented at national level by being given the status of a national standard and by withdrawal of any conflicting national standard". Therefore, a European Standard automatically becomes a national standard in each member country.

European accreditation, calibration and conformity assessments are operated by:

- The European co-operation for Accreditation (EA), founded in 1997, which develops and maintains the EA multilateral agreement of mutual recognition (EA MLA) which is similar to the ILAC MRA in that it seeks to harmonise accreditation infrastructure.

Two other organisations contribute to the maintenance of standards in Europe:

- EUROLAB, formed in 1990, has a number of roles amongst which calibration and conformity assessment feature.
- EURACHEM, founded in 1989, produces guidance documents with the aim of establishing a system for the international traceability of chemical measurements and the promotion of good quality practices.

In the field of legal metrology Europe has a dedicated organisation, The European Cooperation in Legal Metrology (WELMEC). Founded in 1990, WELMEC works to harmonise legal metrology amongst the EU member states and has close links to the OIML (see *Chapter 4*).

Chapter 4. Legal Metrology

Chapter 4. Legal Metrology

> *"If the direct cost of making measurements is large, the indirect cost of making poor measurements must be huge."* J.S. Hunter.

4.1 What is legal metrology?

Legal metrology, perhaps more directly than any other field of measurement science, affects our daily lives. It underpins such things as buying food from a supermarket or switching on an electric kettle in the home. Indeed, there is very little in the modern world that legal metrology does not touch. Despite this very few people outside of the scientific community have heard of it or understand what it does.

Legal metrology is distinct from other forms of metrology in that it encompasses the *application of legal requirements to measurements and measuring instruments.*

Some confusion can arise as to what falls under the umbrella of legal metrology. Simply put, it covers measuring instruments where the accuracy and performance are controlled by legally binding regulations, such as the accuracy of supermarket weighing scales or petrol pumps in a filling station forecourt.

An average sized car, for example, is composed of around 30 000 separate parts often manufactured in different countries. Yet they must all have been machined, with the correct tolerances and specifications, to fit perfectly together in the assembled vehicle. This entire process is highly dependent upon industrial metrology and measurement traceability (see *Chapter 3*), but it does not fall under the scope of legal metrology. When the vehicle's exhaust emissions are checked however, legal metrology is involved as the instrument monitoring these falls under its scope.

Adherence to the output of the legal metrology process ensures the accuracy of, and increases the confidence in, such things as:

- The trade in goods by weight or volume both on a national or international level.
- The metering of energy supplies such as gas and electricity.
- The dosage and purity of medicines.

As well as instilling confidence in regulated measurements, legal metrology also has many other positive benefits for society such as:

- Assuring consumer protection for the citizen.
- Reducing disputes and transaction costs for commerce to provide a level playing field.
- Aiding the collection of government taxes and helping reduce fraud.

4.2 The International Organization of Legal Metrology (OIML)

The signing of the Metre Convention in 1875 ratified a treaty stating that all signatories would use, develop and promote a common measurement system (See Chapter 1). However, the need to ensure international consistency of trade and regulatory measurements led to the establishment of a second treaty organisation in 1955: The International Organization of Legal Metrology (OIML). As of April 2024, 64 member states had ratified the OIML Convention, and 63 other states were corresponding members.

4.2.1 The role of OIML

The scope of OIML is to aid in international harmonisation of the metrology infrastructures that underpin legal and consumer protection worldwide. It does this by:

- Supporting measurement credibility through a shared framework.
- Eliminating technical barriers to trade in measuring instruments.
- Promoting international trade by increasing confidence in measurement capability.

Whilst its original focus was on trade metrology between member states, this was later extended to cover the metrological aspects of health, safety and the environment.

OIML does not enforce metrological regulations but instead accomplishes its goals mainly through the publication of recommendations, reference standards and guidance. However, the signatory nations of the OIML Convention are *morally obliged* to implement the decisions of the International Conference on Legal Metrology (Article VIII) into their legislation or regulations (see *Figure 4.1*).

As metrological harmonisation is one of its central roles this is underpinned by a memorandum of understanding (MoU) with a number of international bodies.

4.2.2 OIML structure

In many respects the general structure of OIML resembles that of the organisations that were founded to administer the Metre Convention (see *Chapter 2*, *Figure 2.2* and *Figure 4.1*).

Figure 4.1. OIML organisational structure.

At the upper echelon is the *International Conference of Legal Metrology* which is the highest decision-making body in the Organisation. This meets every four years and, like the CGPM, consists of individuals drawn from the member nations. Below this sits the *International Committee of Legal Metrology* (CIML) that meets annually with a membership drawn from signatory member nations. The CIML, amongst other things, approves the overall strategy and the adoption and implementation of the output documents of the OIML. The *International Bureau of Legal Metrology* (BIML) is the OIML secretariat and supervises and co-ordinates the project and technical groups and committees which generate OIML's outputs. Members of the CIML and BIML also sit on the CEEMS advisory group (dashed arrows) which liaises and aids in the development of legal metrology in countries with emerging economies. Solid arrows indicate the information flow between divisions.

Unlike most international organisations, OIML has a loose, decentralised structure with a relatively small secretariat, the International Bureau of Legal Metrology (BIML).

The BIML has a wide range of roles such as:

- Supervising and coordinating the OIML's technical work along with publishing and distributing the organisation's documents.
- Publishing the OIML Bulletin and maintaining the OIML web site.
- Organising the meetings of the International Conference of Legal Metrology.
- Organising the meetings of the International Committee of Legal Metrology (CIML).
- Implementing the decisions of OIML Conferences and Committees.

The need to regulate domestic trade and facilitate international trade is a key issue in the development of any economy. The importance of the role of legal metrology in this is recognised by OIML's formation, in 2013, of an Advisory Group on Countries and Economies with Emerging Metrology Systems (CEEMS AG). The Advisory Group provides a platform for CEEMS nations to participate in the activities of the OIML, as well as aiding in the development of the metrological infrastructure in these nations.

One of the main outputs from OIML is the Recommendations (see section 4.2.3) which are the basis of many, if not all, legally binding regulations regarding measurement instruments in signatory states.

4.2.3 The OIML certification system (OIML-CS)

The conformity of measurement instruments on an international scale is of paramount importance in legal metrology. To support this, OIML publishes and maintains a series of technical standards known as Recommendations. These standards are designed to be used as models from which OIML member states can develop regulations. The Recommendations typically establish the required metrological characteristics of certain types of measuring instruments, as well as specifying the methods and equipment needed for checking their conformity.

When a measurement instrument subject to legal metrological control has demonstrated conformance to the applicable Recommendation, under the OIML Certification System (OIML-CS), an OIML certificate is issued. The aim of the certification scheme is to aid the work of the national and regional bodies responsible for evaluation and approval of instruments used for legal metrology.

OIML-CS has two types of certification, 'Scheme A' and 'Scheme B'. The main difference between these is that instruments covered in Scheme A have to demonstrate compliance through accreditation or peer assessment whereas for instruments in Scheme B it is sufficient to demonstrate compliance on the basis of a "self-declaration" with additional supporting evidence.

From April 2024 OIML-CS listed 40 categories of measurement instruments or modules falling under these schemes (https://www.oiml.org/en/oiml-cs/categories).

4.3 WELMEC – the European Cooperation in Legal Metrology

Europe has in place a particularly harmonised legal metrology system which is supported by the work of a second legal entity: the European Cooperation in Legal Metrology e.V. (WELMEC).

WELMEC is a regional legal metrology organisation with membership composed of the representative national authorities responsible for legal metrology in the EU and EFTA countries and countries associated with EU.

WELMEC was originally created in June 1990 by a Memorandum of Understanding (MoU) for cooperation. Originally signed by authorities from 18 countries, new members joined over the following years and WELMEC grew to an association of 38 member organisations.

In order to strengthen and further develop their cooperation, in November 2019 WELMEC members founded a formal legal entity. Since September 2020, all activities of the association are continued by WELMEC e.V. established in Braunschweig (Germany).

The general task of WELMEC is for authorities to cooperate and to interact with stakeholders, in order to establish a common understanding which supports the implementation of a European regulatory framework on metrology. In this regard WELMEC has several memoranda of understanding (MoUs) in place with other European organisations such as the European Cooperation for Accreditation (EA) and the European Association of Metrological Institutes (EURAMET, see Chapter 2) which provide a well-defined framework for the adherence to, or compliance with, OIML Recommendations.

From its initial establishment, WELMEC members have shared a common drive for the free movement of measuring instruments by reducing barriers to trade for a wide range of instruments.

Over the past several years, the metrology directives of greatest interest have been those relating to units of measurement, measuring instruments, non-automatic weighing instruments and pre-packaged goods. However, account has also been taken of other internal market policies and legislation governing aspects such as market surveillance and mutual recognition.

Since its formation some of the most important developments have been:

- Supporting the European legal framework by the continuous publication of detailed technical guides.
- Recognition by the European Commission of WELMEC Guides.
- Identification of relevant normative documents (OIML-Recommendations, European standards) eligible to provide presumption of conformity with the essential requirements of the relevant directives.
- Providing the basis for information exchange for Market Surveillance and Administrative cooperation.
- The promotion of training on the subject of legal metrology, market surveillance and pre-packaged products.

4.4 Regulation for measuring instruments

Most individuals using measurement instruments, such as a gas company meter reader or a person dispensing petrol at a pump, will not be metrology experts. It is the role of government and international bodies to take responsibility for the accuracy of the instruments used.

The local legislative framework, and associated regulations, are dependent on instrument type. Generally, however, regulations fall under three requirement categories: technical, metrological and administrative.

The technical requirements set the general design characteristics for the instrument. These include such things as the simplicity of making unique measurement results, the capability of maintaining their measurement quality over the instrument's operational life, and that risks of tampering or fraud have been reduced as far as possible.

The metrological requirements set the maximum permissible errors for instruments and the operational conditions under which these must be met. Metrological requirements may also specify measuring ranges, and verification procedures.

The administrative requirements, amongst other things, are concerned with how regulations are applied to the instrument for the purpose of ascertaining regulatory compliance. This may include how often, and in what manner, it is tested for conformity to its metrological and technical requirements.

The OIML is an "international standard-setting body" recognised under the World Trade Organization's Technical Barriers to Trade Agreement (WTO TBT agreement). Its Recommendations should therefore be enforced, in the form of legally binding regulations, when appropriate, by all signatories of the TBT Agreement which are OIML member states or economic areas.

Individual or state entities adopting these regulations are said to have conformed to the regulations and are therefore regulatory compliant. As of April 2024, there were 105 active Recommendations issued by OIML for measurement instruments.

4.4.1 European legislative framework for applying legal metrology Recommendations

In 2008 a new legislative framework was introduced in the European Union (EU) in EC Regulations 765/2008, 764/2008 and Decision 768/2008 with the aim of:

- Improving market surveillance rules to better protect both consumers and professionals from unsafe products.
- Setting clear and transparent rules for the accreditation of bodies responsible for conformity assessment.
- Providing stronger and clearer rules on the requirements for the notification of conformity assessment bodies.
- Establishing a common legal framework for industrial products in the form of a toolbox of measures for use in future legislation.
- Clarifying the meaning of the CE marking (see *section 4.4.2*) and enhance its credibility.

4.4.2 European Conformity (CE) markings

Many products require a CE mark before they can be sold in the EU, the European Economic Area (EEA) or in Switzerland (based on an agreement with the EU), the UK after the Brexit has its own system of conformity assessment which might recognise the CE marking.

The EU 2008 legislation covers a variety of areas such as health, safety and environmental protection, and which directive applies is heavily dependent upon the item produced such as the safety aspects regarding the sale of toys. However, where the accuracy of an item is concerned, such as with scientific instruments the products must additionally go through a specific conformity assessment procedure before it can be sold.

4.4.3 Conformity assessment procedure - MID and NAWID

Conformity assessment must demonstrate that all applicable legislative requirements are met, including testing, inspection and certification and:

- Follows a product specific procedure that is detailed in the applicable legislation.
- Is performed by notified bodies that are accredited to demonstrate their competence to conduct conformity assessments.

In the European Union there are two specific directives that apply to measuring instruments: Directive 2014/32/EU the Measuring Instruments Directive (MID) and Directive 2014/31/EU on Non-Automatic Weighing Instruments (NAWI).

The MID directive covers 10 types of measuring instruments. NAWI instruments are defined as those which require the intervention of an operator and thus this directive covers a wide range of products, from shop scales to the weighing of patients for medical purposes, but generally falls into 4 categories (see *Table 4.1*).

Table 4.1. Devices applicable to MID or NAWI directives.

Types of instruments covered by MID
MI-001: P Water meters
MI-002: Gas Meters & Conversion Devices
MI-003: Active Electrical Meters
MI-004: Thermal Energy Meters
MI-005: Measuring systems for Liquids other than Water
MI-006: Automatic Weighing Instruments
MI-007: Taximeters
MI-008: Material Measures
MI-009: Dimensional Measuring Instruments
MI-010: Exhaust Gas Analysers

Types of classes covered by NAWI
Class 1: special accuracy, typically for precious stones or metals
Class 2: high accuracy, typically for pharmaceutical products
Class 3: medium accuracy, for everyday trade purposes
Class 4: ordinary accuracy for approximate weighing

The Measuring Instruments Directive (MID) covers 10 classes of measuring instruments (upper list). The Non-Automatic Weighing Instruments directive (NAWI) covers a broader range of instruments as these are classified as any instrument that requires the intervention of an operator but can be broken down into 4 general classes on the basis of their accuracy (lower list).

When a measuring instrument has been shown to comply to the regulations by a notified body then, along with the CE mark, a supplementary metrology "M" mark is affixed to the device (see *Figure 4.2*). Along with the "M" is placed the date of the year the mark was affixed, and an identifier of the notified bodies concerned with the conformity assessment. In some EU states the year is used to determine the reverification period of the instrument.

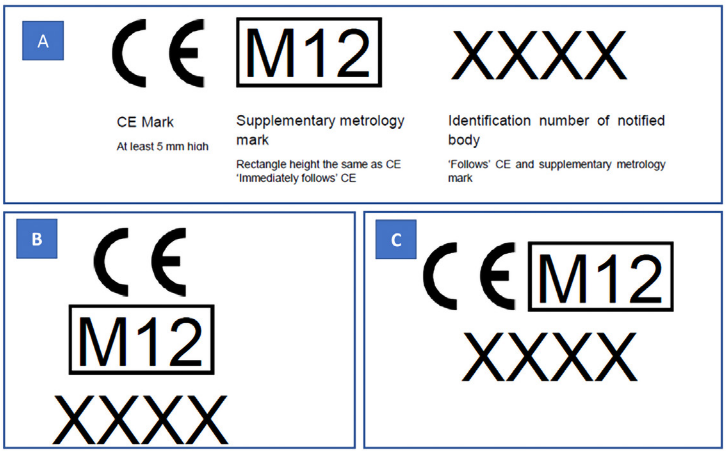


Figure 4.2. Examples of various CE marks to show measurement device conformity.

The CE mark can be considered as a "metrological passport" allowing free access of trade within the EEA and its respective markets. It can take a number of forms (examples are shown in A-C) but regardless of which it must be of a minimum size and clearly visible. Following the CE mark, on measurement instruments, is the supplementary metrological mark "M" which is followed by the last two digits of the year it was affixed (the example shown is from 2012). After the supplementary mark is the identification number of the notified body who performed the conformity assessment. This figure was adapted from the European Cooperation in Legal Metrology application guide **WELMEC 8.21 Issue 1 May 2012**.

4.4.4 Regulatory compliance in trade: pre-packaged goods

Whilst many trade regulations will fall under the NAWI directive, such as items bought loose by weight, separate legislation exists in Europe for pre-packaged goods.

In the EU these are defined as: "the combination of a product and the individual package in which it is prepacked" and, since 2007, fall under Directive 2007/45/EC and amended by Directive 76/211/EEC. These directives contain the requirements that pre-packaged goods must fulfil, such as containing an average quantity which is not less than that marked on the package.

When all directives are met the packages are marked with the ℮ mark indicating that the item is compliant with EU law. Like the CE mark the ℮ mark can be considered as a 'metrological passport' allowing free access of trade within the EEA and its respective markets. The purpose of the ℮ mark is to protect consumers from 'short measure', meaning that they are not being undersold goods.

There is no set weight or quantity for pre-packaged goods, except for such things as stipulated wines and spirits, but the ℮ mark is not required for packages of less than 5 g or 5 ml or greater than 10 kg or 10 L.

It should be noted that whilst Directive 2007/45/EC, and its associated regulations, concerning the ℮ marking, are important there are also a number of other relevant legal requirements for pre-packaged items, such as Directive 75/324/EEC on Aerosol dispensers, or Directive 2000/13/EC on the Labelling, presentation and advertising of foodstuffs.

4.4.5 Market surveillance for measurement instruments

Market surveillance occurs after a product has entered the European market to ensure that the instrument continues to be compliant to the relevant legislation. As a large number of products exist, and more may appear in the future, the European Union adopts a broad-based, loose, legislative framework to cover this (see *REGULATION (EC) 765/2008*).

It is the role and responsibility of individual EU member states to perform market surveillance of products in their country; and amongst other things they are required to guarantee that:

- Products placed on the market are monitored.
- Market surveillance authorities have the necessary powers, resources and knowledge to perform their functions.
- Market surveillance programs are established, implemented, and periodically updated.
- Surveillance activities are reviewed and assessed at least every four years for functionality.

In the specific case of measurement instruments, market surveillance begins after its first appearance in the market which is defined as *“making available for the first time in the Community an instrument intended for an end user, whether for reward or free of charge”* (Directive 2004/22/EC).

The market surveillance authorities are charged under REGULATION (EC) 765/2008 with a number of responsibilities in regard to measurement instruments such as:

- Performing appropriate checks on the characteristics of the instrument.
- Performing documentary checks and, where appropriate, physical and laboratory checks using an adequate number of samples and scales.
- Taking into account established principles of risk assessment, complaints and other information during checks.

If the authorities of a member nation discover a systematic failure in the instrument, so that it either no longer complies with regulations, or is likely to pose a risk, then further steps are taken. If the manufacturer, or their representatives cannot correct the matter, the instrument is removed from the market.

Glossary of Terms

Glossary of Terms

Absolute measurement error: When it is necessary to distinguish ‘error’ from ‘**relative error**’ the former is sometimes called an ‘absolute’ error of measurement.

Accreditation: An attestation by an **Accreditation Body** that a **Conformity Assessment** Body meets the requirements set by harmonised standards and, where applicable, any additional requirements including those set out in relevant sectoral schemes, to carry out a specific conformity assessment activity (Regulations (EC) No 765/2008 definition).

Accreditation Body: An organisation that confirms, through **accreditation**, the competency of other groups or organisations to issue credentials or certify third parties against official standards. Accreditation bodies exist at both the international and national levels.

Accredited laboratory: A laboratory which meets the standards of an approved **Accreditation Body**.

Accuracy, Measurement accuracy: Closeness of agreement between a measured **quantity value** and a true **quantity value** of a **measurand**.

Accuracy class: Class of **measuring instruments** or **measuring systems** that meet stated metrological requirements that are intended to keep measurement errors or instrumental measurement uncertainties within specified limits under specified operating conditions.

Accuracy of a measuring instrument: The ability of a **measuring instrument** to give responses close to a true value.

Artefact: An object fashioned by human hand. Examples of artefacts made for taking measurements are a weight and a measuring rod.

Artefact calibration: A measurement process that assigns values to the property of an **artefact** relative to a **reference standard**(s).

Assay: Quantification of a chemical or biological element obtained by an empirical dose–response relationship.

Base quantity: **Quantity** in a conventionally chosen subset of a given system of quantities, where no subset quantity can be expressed in terms of the others.

Base unit: Measurement unit that is adopted by convention for a **base quantity**. In the **SI** the metre is the base unit of length, for example.

Calibration: Set of operations that establish, under specified conditions, the relationship between the **quantity value** of a **measurement standard** and its **measurement uncertainties**.

Calibration certificate: Official record of a **calibration**.

Calibration hierarchy: Sequence of calibrations from a reference to the final measuring system, where the outcome of each calibration depends on the outcome of the previous calibration (see also hierarchy of standards)

Calibration history, measuring equipment: Complete registration of the results from the calibration of a piece of measuring equipment, or measuring artefact, over a long period of time, to enable the evaluation of its long-term stability.

Calibration interval: Time interval between two consecutive calibrations of a measuring instrument.

Calibration laboratory: A laboratory that has been accredited by an accreditation body to perform calibrations, usually under the technical standard ISO/IEC 17025.

Calibration and Measurement Capabilities (CMCs): An indication of a laboratory's normal ability for a type of measurement. Statements on the outcomes of the CIPM MRA that inform upon the measurement capabilities of the NMIs or DIs in performing a particular measurement. These results are published and maintained in the publicly available BIPM Key comparison database (KCDB).

Calibration standards: A standard used to calibrate working standards or measuring instruments which is directly traceable back to the national standard for that SI unit.

CE-mark(ing): A symbol applied to products to indicate that they conform with relevant EU directives regarding health and safety or environmental protection.

CIPM MRA, CIPM Mutual Recognition Arrangement: The framework through which National Metrology Institutes demonstrate the international equivalence of their measurement standards and the calibration and measurement certificates they issue. The outcomes of the arrangement are the internationally recognised (peer-reviewed and approved) Calibration and Measurement Capabilities (CMCs) of the participating institutes.

CMCs, Calibration and Measurement Capabilities: see Calibration and Measurement Capabilities (CMCs).

Coherent derived unit: Derived unit that, for a given system of quantities and for a chosen set of base units, is a product of powers of base units with no other proportionality factor than one.

Compound standard: A set of similar material measures or measuring instruments that, through their combined use, constitutes one standard called a compound standard.

Conformity: Compliance with standards, rules, or laws.

Conformity assessment: An activity that provides demonstration that specified requirements relating to a product, process, system, person or body are fulfilled, such as testing, inspection, certification of products, personnel and management systems.

Conventional value of a quantity: Quantity value attributed by agreement to a quantity for a given purpose, for example the 'standard acceleration due to free fall'.

Correction factor: Factor by which the uncorrected measuring result is multiplied to compensate for a **systematic error**.

Correction value: Value which added algebraically to the uncorrected result of a measurement compensates for a **systematic error**.

Coverage factor: A number greater than 1 by which the combined standard **measurement uncertainty** is multiplied to obtain an **expanded measurement uncertainty**.

CRM, Certified Reference Material: **Reference material** accompanied by a certificate issued by an authoritative body which provides one or more specified property values with associated uncertainties and demonstrated traceability established using valid procedures.

Derived quantity: Quantity, in a system of quantities, defined in terms of the base quantities of that system.

Derived unit: The measurement unit for a **derived quantity**.

Designated Institute: See DI, designated institute.

Detector: A device or substance that indicates the presence of a phenomenon, body or substance when a threshold value is exceeded, without necessarily providing a value of an associated **quantity**.

Deviation: **Quantity value** minus its **reference value**.

DI, Designated Institute: An institute designated by a national government or its **NMI** to hold specific national standards, and which usually participates in the **CIPM MRA**.

Directives (EU): A directive is a legal act of the European Union (EU) which requires member states to achieve a particular result without dictating the means of achieving that result.

Drift: Continuous or incremental change in indication over time due to changes in the metrological properties of a **measuring instrument**, **measuring system** or **reference material**.

EA MLA: A multilateral agreement by the **European co-operation for Accreditation (EA)**. Signed between national **accreditation bodies**, members recognise the equivalence, reliability and therefore acceptance by the European market, of certification, verification, inspection and **calibration certificates** and test reports issued by accredited **conformity assessment** bodies.

℮ mark, (*quantité estimée*), estimated Sign: Found on some pre-packed goods in Europe indicating they are compliant to or fulfils European Union EU Directive 76/211/EEC.

Etalon: A **measurement standard**.

Expanded measurement uncertainty, overall uncertainty: A measure of uncertainty that defines an interval about the **measurement result** **Y** within which the value of the **measurand** **Y** can be confidently asserted to lie. Product of a combined standard **measurement uncertainty** and a **coverage factor** larger than the number one.

Explicit-constant formulation: Definition of an **SI unit** where the unit is defined indirectly by specifying explicitly an exact value for a well-recognised fundamental constant.

GLP, Good Laboratory Practice: A set of principles to assure the quality and integrity of non-clinical laboratory studies that are intended to support research or marketing permits for products regulated by government agencies. In Europe laboratories are **accredited** in accordance with regulations provided by the Organisation for Economic Co-operation and Development (OECD).

GUM, Guide to the expression of uncertainty in measurement: Guide, published by the Joint Committee for Guides in **Metrology** Working Group 1 (JCGM/WG 1). It describes the best practice for making **uncertainty** calculations. It is ISO recommended and is accepted by such entities as **accreditation bodies**. The JCGM/WG 1 also produced a series of documents to accompany this (https://www.bipm.org/en/publications/guides/gum.html).

Hierarchy of Standards: A commonly used term describing an order of **measurement standards** ranging from the **international standard** (at the top level) down to routinely used **working standards** (at the bottom level).

IAF MLA: Multilateral Recognition Arrangement of the International Accreditation Forum (IAF) to ensure mutual recognition of accredited certification between signatories to the MLA, and subsequently acceptance of accredited certification in many markets based on one **accreditation**.

ILAC MRA, International Laboratory Accreditation Cooperation Mutual Recognition Arrangement: A method by which laboratory **accreditation bodies** can be confident in the work performed by other accreditation bodies. Signatories to the ILAC MRA are peer evaluated in accordance with the requirements of ISO/IEC 17011 standard to demonstrate their competence. They also perform accreditation of **conformity assessment** bodies against the relevant international standards. Such as ISO/IEC 17025 for **calibration** and testing laboratories, ISO/IEC 15189 for medical testing laboratories and ISO/IEC 17020 for inspection bodies.

Imperial (measurement) system: **Measurement system** used officially in Great Britain from 1824 until the adoption of the **metric system** in 1965. The United States Customary System of weights and measures is derived from it.

Indication: **Quantity value** provided by a **measuring instrument** or system, a measuring instruments signal or response.

Industrial (Applied, technical) metrology: One of the three main branches of **metrology**. It is concerned with the application of measurement to manufacturing and other processes and their use in society including the suitability of **measurement instruments**, their **calibration** and quality control.

Instrument constant: Coefficient by which the direct indication of a **measuring instrument** must be multiplied to give the indicated value of the **measurand** or be used to calculate the value of the **measurand**.

International Accreditation bodies: **Accreditation** system established worldwide by the International Accreditation Forum (IAF) and the International Laboratory Accreditation Cooperation (ILAC).

International measurement standard: **Measurement standard** recognised by signatories to an international agreement and intended to serve worldwide.

KCDB, BIPM Key Comparison Database: Supports the **CIPM MRA** and is composed of four appendices (A-D) which includes National Metrology Institutes and Designated Institutes which are participants and the outcome of the **key** and **supplementary comparisons**.

Key Comparisons (KCs): Comparison studies composed of two types: CIPM key comparisons and RMO key comparisons. The CIPM key comparisons are 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 Member States. The CIPM key comparisons deliver the '**reference value**' for the chosen key **quantity**. The RMO key comparisons are of regional scope and are open to laboratories of Associates as well as Member States. These key comparisons deliver complementary information without changing the **reference value**.

Laboratory accreditation: is an international recognised means of determining the technical competence of laboratories to perform specific types of testing, measurement and **calibration**.

Legal metrology: One of the three main types of **metrology**, legal metrology is the application of legal requirements to measurements and **measuring instruments**.

Maintenance of a measurement standard: Set of measures necessary to preserve the metrological characteristics of a **measurement standard** within stated limits.

Market surveillance: A monitoring approach to ensure that products on the market are in **conformity** with the applicable law.

Material measure: Device intended to reproduce or supply, in a permanent manner during its use, one or more known **quantity value** such as a standard weight, a volume measure, a gauge block, or a **certified reference material**.

Matrix reference material: A **reference material** that is characteristic of a real sample. Matrix materials are intended to be used in conjunction with the analysis of real samples of the same or a similar matrix.

Maximum permissible error (of a measuring instrument): Extreme values for a **measurement error** with respect to a known reference **quantity value** permitted by specifications, regulations, etc. for a given measurement, **measuring instrument** or **measurement system**.

Measurand: The quantity which is subject to **measurement**.

Measurement: Process of experimentally obtaining one or more **quantity values** that can reasonably be attributed to a quantity. Set of operations for the purpose of determining the value of a **quantity**.

Measurement accuracy: see **Accuracy**.

Measurement error: Measured **quantity value** minus a reference **quantity value**.

Measurement Precision: The closeness of agreement between indications or measured **quantity** values obtained by replicate **measurements** on the same or similar objects under specified conditions.

Measurement procedure: Detailed description of a **measurement** according to one or more measurement principles and to a given measurement method, based on a measurement model and including any calculation to obtain a **measurement result**.

Measurement repeatability: Measurement **precision** under a set of repeatability conditions of **measurement**. Also see Repeatability (of measurement results)

Measurement result: Set of **quantity values** being attributed to a **measurand** together with any other available relevant information.

Measurement standard, etalon: **Realisation** of the definition of a given **quantity**, with stated **quantity value** and associated **measurement uncertainty**, used as a reference. The realisation may be provided by a material measure, **measuring instrument**, **reference material** or **measuring system**.

Measurement system: Set of one or more **measuring instruments** and often other devices, including any reagent and supply, assembled and adapted to give information used to generate measured **quantity** values within specified intervals for quantities of specified kinds.

Measurement traceability: An unbroken chain of comparisons relating an instrument's **measurements** to a known standard. In the **metric system** this traceability is ideally to one of the seven base **SI units**.

Measurement uncertainty: A non-negative parameter indicating the expression of the statistical dispersion of the values attributed to a measured **quantity** such as standard deviation. A **measurement result** is not complete unless accompanied by a statement of the associated uncertainty, preferably according to GUM guidelines.

Measurement unit: Real scalar **quantity**, defined and adopted by convention, with which any other quantity of the same kind can be compared to express the ratio of the two quantities as a number.

Measuring instrument: Device intended to be used to make **measurements**, alone or in conjunction with one or more supplementary devices.

Measuring range: Set of values of **measurands** for which the error of a **measuring instrument** is intended to lie within specified limits.

Metre Convention: International diplomatic treaty established in 1875 for the purpose of ensuring a globally uniform system of measuring units.

Metric system: Measuring system based on the metre, kilogram and other **base units**. Officially adopted by the French government on 7 April 1795. Subsequently developed into the **SI system**.

Metrology: From the Greek word metron meaning “a measure”. The science of **measurement** and its application. Metrology can be divided into three main types: **Industrial metrology**, **Legal metrology** and **Scientific metrology**.

MID, Measuring Instruments Directive: **Directive** 2014/32/EU amended by Directive 2015/13/EU. European Union (EU) directive which seeks to harmonise the **legal metrology** aspects of **measuring instruments**.

Mise en pratique: Method (experimental) by which a measure is realised.

MKSA system: A system of measurement units based on the **M**etre, **K**ilogram, **S**econd and **A**mpere. In 1954 the system was extended to include the Kelvin and the Candela. It was then given the name “**SI system**” in 1960.

MRA, Mutual Recognition Agreement: An agreement between two or more parties that recognises the work performed by the other(s) as if it were their own. In **metrology** it mainly applies to **conformity assessment** procedures and is generally applied under ISO/IEC Guide 68: 2002(R2014).

Mutual Recognition Arrangement, CIPM: See CIPM, MRA

National Measurement standard: **Measurement standard** recognised by a national authority to serve in a state or economy as the basis for assigning **quantity values** to other measurement standards for the kind of **quantity** concerned. In some circumstances the national measurement standard can also be the **international measurement standard**.

NAWI, Non-Automatic Weighing Instruments directive: **Directive** 2014/31/EU. European Union (**EU**) directive which seeks to harmonise the **legal metrology** aspects of weighing instruments that require the intervention of an operator.

NMI, National Metrology Institute: An institute designated by national decision to develop and maintain **national measurement standards** for one or more **quantities**. An NMI represents the country internationally in relation to the national metrology institutes of other countries, in relation to the Regional Metrology Organisations (RMOs) and to the BIPM.

Nominal Property value: Property of a phenomenon, body, or substance, where the property has no magnitude, such as the sex of a human being or the colour of a paint sample.

Notified body: An organisation designated by an EU country to assess the **conformity** of certain products before being placed on the market. These bodies carry out tasks related to **conformity assessment** procedures set out in the applicable legislation, when a third party is required.

OIML-CS, International Organisation of Legal Metrology Certification System: A voluntary system for issuing, registering and using OIML Certificates and their associated OIML type evaluation/test reports for types of **measuring instruments** based on the requirements of OIML. Introduced in 2018 it replaced the OIML Basic Certificate System and the Mutual Acceptance Arrangement (MAA) certificate system.

OIML Recommendations, Recommendations: International recommendations, which are intended as model regulations for a number of categories of measuring instruments, and which OIML Member States are morally obliged to implement as far as possible.

Performance testing (laboratory): Determination of the testing capability of a laboratory, by comparing tests performed between laboratories.

Physical constant, fundamental physical constant: A physical constant that is believed to be universal in nature and invariant over time.

Precision: See **Measurement Precision**.

Primary measurement standard, Primary metrological standard: A **measurement standard** that is designated or widely acknowledged as having the highest metrological qualities and whose **measurement results** are determined without reference to other standards of the same **quantity** in the same **measurement range**. The primary standard is the definitive definition or **realisation** of the unit of measure.

Primary method: A method of the highest metrological quality which when implemented can be described and understood completely, and for which a complete **uncertainty** budget can be provided in **SI units**, the results of which can therefore be accepted without reference to a standard for the **quantity** being measured.

Primary reference material: **Reference material** that has the highest metrological qualities and whose value is determined by the use of a primary method.

Principle of measurement: The scientific foundation of a method of **measurement**. A phenomenon serving as the basis of a measurement.

PTS, Proficiency Testing Schemes: A means by which laboratories capabilities are checked through the analysis of test samples.

Quantity: The property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference. The concept ‘quantity’ may be generically divided into, for example, ‘physical quantity’, ‘chemical quantity’, and ‘biological quantity’, or base quantity and **derived quantity**.

Quantity value: Number and reference together expressing magnitude of a **quantity**.

Random measurement error: Component of **measurement error** that in replicate **measurements** varies in an unpredictable manner.

Realisation: The conversion of a unit measure from its definition into reality.

Reference conditions: Operating conditions prescribed for evaluating the performance of a **measuring instrument** or measuring system or for comparison of **measurement results**.

Reference material (RM): material, sufficiently homogeneous and stable with reference to specified properties, which has been established to be fit for its intended use in **measurement** or in examination of **nominal properties**.

Reference standard: **Measurement standard** designated for the **calibration** of other measurement standards for **quantities** of a given kind in a given organisation or at a given location.

Reference value, reference quantity value: **Quantity value** used as a basis for comparison with values of **quantities** of the same kind.

Relative error: **Measurement error** divided by a true value of the **measurand**.

Repeatability: The agreement within sets of **measurements** performed by the same individual under the same conditions.

Repeatability (of results of measurements): Closeness of the agreement between the results of successive **measurements** of the same **measurand** carried out under the same conditions of measurement.

Reproducibility (of results of measurements): Closeness of agreement between the results of **measurements** of the same **measurand** carried out under changed conditions of measurement.

RM, Reference material: See **reference material**.

Scientific metrology, fundamental metrology: One of the three main classifications of **metrology** dealing with the establishment of **measurement** units, unit systems, the development of new measurement methods, **realisation** of **measurement standards** and the transfer of **traceability** from these standards.

Secondary standard: **Measurement standard** established through **calibration** with respect to a **primary measurement standard** for a **quantity** of the same kind.

SI system, (*Le Système International d'Unités*), The International System of Units: International decimal system of weights and measures derived from, and extending, the **metric system** of units. Adopted by the 11th **General Conference on Weights and Measures** in 1960, it is abbreviated SI in all languages.

SI unit: A **unit** in the **SI system**.

Stability: Property of a **measuring instrument**, whereby its metrological properties remain constant in time.

Standard deviation, experimental: Parameter ***s*** for a series of ***n*** **measurements** of the same **measurand**, characterises the dispersion of the results and is given by the formula for standard deviation.

Supplementary Comparisons (SCs): A comparison, usually carried out by a RMO to meet specific needs not covered by **key comparisons**. Consultative Committees may however decide to run a supplementary comparison when there are only few participants capable of measuring the required **quantity** (none sharing the same RMO), when no link can be made to an RMO comparison or when the distribution of samples to measure is a constraint.

Supplementary metrology "M" mark: An additional marking added alongside a **CE marking** to indicate the instrument is regulated by one of the metrology **directives**.

System of measurement units: Set of **base units** and **derived units**, together with their multiples and submultiples, defined in accordance with given rules, for a given system of **quantities**.

Systematic error: Component of **measurement error** that for repeated **measurements** remains constant or varies in a predictable manner.

TBT, Technical Barrier to Trade: Non-tariff barriers that discriminate against imported products.

Technical standards: An established norm or requirement in regard to technical systems. It is usually a formal document that establishes uniform engineering or technical criteria, methods, processes, and practices.

Testing: Technical procedure consisting of the determination of one or more characteristics of a given product, process or service, in accordance with a specified procedure.

Traceability chain: Sequence of **measurement standards** and **calibrations** that is used to relate the **measurement result** to the reference.

Traceability, metrological: The property of a **measurement result** whereby the result can be related to a reference through a documented unbroken chain of **calibrations**, each contributing to the **measurement uncertainty**.

Transfer device, Transfer measurement device: Device used as an intermediary to compare **measurement standards**.

Travelling standard: **Measurement standard**, sometimes of special construction, intended for transport between different locations. Some travelling standards are used as **transfer devices**.

Uncertainty (of measurement): See **Measurement uncertainty**.

Uncertainty budget: An itemised table of components that contributes to the **uncertainty in measurement results**.

Unit of measurement: See Measurement unit.

Verification: Provision of objective evidence that a given item fulfils specified requirements.

VIM, International Vocabulary of Metrology: A vocabulary, developed at the international level by the most important standardisation bodies, metrology organisations and **accreditation** laboratories. It contains the terms associated to basic and general concepts of **metrology**, with many examples from different fields of application. VIM, and a document containing definitions with informative annotations developed by the JCGM-WG2, can be downloaded from the BIPM website: publications - BIPM.

Working range: Set of values of **measurands** for which the error of a **measuring instrument** is intended to lie within specified limits.

Working standard: **Measurement standard** that is routinely used to calibrate or verify **measuring instruments** or measuring systems.

WTO TBT agreement: An international treaty administered by the World Trade Organisation (WTO) to ensure that technical regulations, standards, testing, and certification procedures do not create unnecessary obstacles to trade.

Appendix 1:

SI Units

Appendix 1: SI Units

SI Derived Units

The seven SI units can be used to measure more than just the base measurements that these represent, such as length. When a measurement is made from products or powers of these base units then they generate derived units. When a measurement is generated by means of multiplication and exponentiation of other units *but not multiplied by any scaling factor other than one* these are called coherent derived units (see *Table A1.1* for some examples).

Table A1.1 Examples of SI coherent derived units.

Name of derived quantity	Typical symbol of quantity	SI coherent derived unit expressed in terms of base units
area	A	$\mathrm{m^{2}}$
volume	V	$\mathrm{m^{3}}$
speed, velocity	v	$\mathrm{m\ s^{-1}}$
acceleration	a	$\mathrm{m\ s^{-2}}$
wavenumber	σ	$\mathrm{m^{-1}}$
density, mass density	ρ	$\mathrm{kg\ m^{-3}}$
surface density	ρ_A	$\mathrm{kg\ m^{-2}}$
specific volume	v	$\mathrm{m^{3}\ kg^{-1}}$
current density	j	$\mathrm{A\ m^{-2}}$
magnetic field strength	H	$\mathrm{A\ m^{-1}}$
amount of substance concentration	c	$\mathrm{mol\ m^{-3}}$
luminance	L_v	$\mathrm{cd\ m^{-2}}$
refractive index	n	1
relative permeability	m_r	1

Dimensionless SI units

Certain quantities are defined as the *ratio* of two quantities of the same kind and are thus dimensionless or have a dimension that may be expressed by the number one. An example of this is refractive index (n) which is defined as the ratio of the velocity of light in a vacuum (c) to the velocity of light in that medium (v) i.e.: $n = c/v$. The values of all such quantities are simply expressed as numbers, and the unit one is not explicitly shown. There are also some quantities that are defined as a more complex product of simpler quantities in such a way that the product is dimensionless. The Reynolds number (*Re*), for example, is an important dimensionless quantity in fluid mechanics used to help predict flow patterns in different fluid flow situations. The Re number is the *ratio* of inertial forces to viscous forces within a fluid and thus the unit may be considered as the number one, which is a dimensionless derived unit.

Another class of dimensionless quantities are values that represent a *count* and may include the number of atoms in a molecule, the degeneracy (number of energy levels) and partition function in statistical thermodynamics (number of thermally accessible states). All these counting quantities are also described as being dimensionless, or of dimension one, and are taken to have the SI unit one. The unit of counting quantities cannot be described as a derived unit expressed in terms of the base units of the SI. For such quantities, the unit one may instead be regarded as a further base unit.

In a few cases a special name is given to the unit one to facilitate the identification of the quantity involved. This is the case for the radian and the steradian. The radian and steradian have been identified by the CGPM as special names for the coherent derived unit one, to be used to express values of plane angle and solid angle, respectively, and are therefore included in *Table A1.1* (coherent derived units).

SI prefixes

Over the period 1960 to 1991 the CGPM added a number of prefixes to decimal multiples and submultiples of SI units (see *Table A1.2*) along with a number of rules on their use:

- Prefixes refer strictly to powers of 10 and no other power.
- Prefixes must be written without space in front of the symbol of the unit. For example, centimetre is written as cm and not c m.
- Do not use combined prefixes. For example, 10^{-6} kg must be written as 1 mg not 1 μkg.
- A prefix must not be written alone. For example, $10^9/\mathrm{m}^3$ must not be written as $\mathrm{G/m}^3$.
- When a prefix symbol is added to a unit symbol it *constitutes a new inseparable* unit symbol that can be raised to a positive or negative power and that can be combined with other unit symbols to form compound unit symbols. For example, the prefix kilo can be added to metre to give the kilometre (km) unit.

The exception to these prefixes is the base unit the kilogram. For historical reasons no prefix of multiples or submultiples is attached to this unit; instead, they are formed by attaching prefix names to the unit’s name “gram“, and prefix symbols to the unit symbol „g“.

Table A1.2 Approved SI prefix names and symbols.

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
10^{27}	ronna	R	10^{-27}	ronto	r
10^{30}	quetta	Q	10^{-30}	quecto	q

SI derived units with special names

For many derived units their nomenclature reflects their origin i.e. "square metre" (m^2) for area. For those derived units whose name does not reflect their origin (e.g., the unit of frequency, hertz) a special name is dictated to simplify their expression. There are currently 22 of these units (*Table A1.3*).

Table A1.3 The 22 SI units with special names and symbols.

Derived quantity	Special name of unit (symbol)	Unit expressed in terms of other SI units	Unit expressed in terms of base units
plane angle	radian (rad)	1	m/m
solid angle	steradian (sr)	1	m^2/m^2
frequency	hertz (Hz)		s^{-1}
force	newton (N)		$kg\ m\ s^{-2}$
pressure, stress	pascal (Pa)	N/m^2	$kg\ m^{-1}\ s^{-2}$
energy, work, amount of heat	joule (J)	N m	$kg\ m^2\ s^{-2}$
power, radiant flux	watt (W)	J/s	$kg\ m^2\ s^{-3}$
electric charge	coulomb (C)		A s
electric potential difference	volt (V)	W/A	$kg\ m^2\ s^{-3}\ A^{-1}$
capacitance	farad (F)	C/V	$kg^{-1}\ m^{-2}\ s^4\ A^2$
electric resistance	ohm (Ω)	V/A	$kg\ m^2\ s^{-3}\ A^{-2}$
electric conductance	siemens (S)	A/V	$kg^{-1}\ m^{-2}\ s^3\ A^2$
magnetic flux	weber (Wb)	V s	$kg\ m^2\ s^{-2}\ A^{-1}$

magnetic flux density	tesla (T)	Wb/m^2	kg s^{-2} A^{-1}
inductance	henry (H)	Wb/A	kg m^2 s^{-2} A^{-2}
Celsius temperature	Degree Celsius (°C)		K
luminous flux	lumen (lm)	cd sr	cd sr
illuminance	lux (lx)	lm/m^2	cd sr m^{-2}
activity referred to a radionuclide	becquerel (Bq)		s^{-1}
absorbed dose, specific energy (imparted), kerma	gray (Gy)	J/kg	m^2 s^{-2}
dose equivalent	sievert (Sv)	J/kg	m^2 s^{-2}
catalytic activity	katal (kat)		mol s^{-1}

Units outside of the SI

The SI base units and their derivatives are used internationally and have the additional advantage that unit conversions are not required when inserting values into quantity equations. However, the SI system is a relatively recent advancement in metrology and non-SI units appear in the literature and some, such as the nautical knot or the units of time, are deeply embedded in human culture. Furthermore, in some branches of physics it is useful to use non-SI units - such as the use of CGS-Gaussian units in electromagnetic theory applied to quantum electrodynamics and relativity. It should be noted though that when non-SI units are used their advantages are lost. Table A1.4 lists non-SI units accepted for use with the international system of units. There are other units which may have to be experimentally determined or still in common use; for a more detailed list please refer to BIPM literature on this: SI brochure.

Table A1.4 Non-SI units accepted for use with the SI.

Quantity	Name of unit (symbol)	Value in SI units
time	minute (min) hour (h) day (d)	1 min = 60 s 1 h = 60 min = 3600 s 1 d = 24 h = 86 400 s
length	astronomical unit (au)	1 au = 149 597 870 700 m
plane and phase angle	degree (°) minute (‘) second (“)	$1^\circ = (\pi/180)$ rad $1' = (1/60)^\circ = (\pi/10\,800)$ rad $1'' = (1/60)' = (\pi/648\,000)$ rad
area	hectare (ha)	1 ha = 1 hm^2 = 10^4 m^2

volume	**litre (l, L)**	**1 l = 1 L = 1 dm^3 = 10^3 cm^3 = 10^{-3} m^3**
mass	**tonne (t) Dalton Da**	**1 t = 10^3 kg 1 Da = 1.660 539 066 60(50) × 10^{-27} kg**
energy	**electronvolt (eV)**	**1 eV = 1.602 176 634 × 10^{-19} J**
Logarithmic ratio quantities	**neper (Np) Bel (B) decibel (dB)**	**See BIPM SI Brochure**

Writing unit symbols and names and expressing the values of quantities

The General principles for the writing of unit symbols and numbers were first given by the 9th CGPM (1948). Since then, the ISO, IEC and other international bodies have elaborated on their correct use which aids in the readability and understanding of scientific and technical papers. Some of the most important points are highlighted below.

Unit symbols

- Unit symbols are printed in roman (upright) type regardless of the type used in the surrounding text.
- Symbols are not capitalised except when the first letter of a symbol is:
  i) the name of the unit comes from a person's name (with the exception of the litre).
  ii) the symbol is the beginning of a sentence.
  For example: the unit kelvin is written as the symbol K (not k).
- Symbols must remain unchanged in the plural – no "s" is added.
- Symbols are never followed by full stops unless at the end of a sentence.
- Units combined by the multiplication of several units must be written with a centred dot or a space. For example: N · m or N m (not Nm).
- Units combined by the division of one unit with another must be written with a slash or a negative exponent.
  For example: m/s or m · s^{-1}.
- Combined units must only include one slash. The use of parenthesis or negative exponents for complex combinations is permitted.
  For example: m/s^2 or m · s^{-2} but not m/s/s
  For example: m · kg/(s^3 · A) or m · kg · s-3 · A^{-1} but neither m · kg/s^3/A nor m · kg/s^3 · A.
- Symbols must be separated from the numerical value they follow by a space. For example: 5 kg but not 5kg.
- Unit symbols and unit names should not be mixed. For example: kilogram per cubic metre but not kilogram per m^3.

Equations containing quantity values

- Mathematical operations should only be applied to unit symbols and not unit names. For example: (kg/m^3) but not (kilogram/cubic metre).

- It should be clear to which unit symbol a numerical value belongs and which mathematical operation applies to the value of a quantity.
  For example: 35 cm × 48 cm not 35 × 48 cm.
  For example: 100 g ± 2 g not 100 ± 2 g.

- Symbols for quantities are generally single letters set in an italic font, although they may be qualified by further information in subscripts or superscripts or in brackets.

- Recommended names and symbols for quantities are listed in many standard references. However, symbols for quantities are recommendations (in contrast to symbols for units, for which the use of the correct form is mandatory).

- In specific circumstances authors may wish to use a symbol of their own choice for a quantity, for example in order to avoid a conflict arising from the use of the same symbol for two different quantities – such as the use of the letter k in an algebraic equation regarding temperature. In such cases, the meaning of the symbol must be clearly stated.

- Neither the name of a quantity, nor the symbol used to denote it, should imply any particular choice of unit.

- Symbols for units are treated as mathematical entities. In expressing the value of a quantity as the product of a numerical value and a unit, both the numerical value and the unit may be treated by the ordinary rules of algebra.

Appendix 2:

Measurement Uncertainty

Appendix 2: Measurement Uncertainty

It is important to realise that every measurement is incomplete without a statement regarding the measurement's *uncertainty*. It is important to note that uncertainty is not the same as *measurement error* – error is the difference between a measured value and the 'true' value whereas uncertainty is a quantification of the 'doubt' about the measurement. Measurement mistakes, tolerances and specifications are also not 'uncertainties' in this context.

Calculating measurement uncertainty

The environment of an object may affect its measurement (e.g temperature, humidity, vibration, gravity or the presence of magnetic fields). It may be the influenced by the individual making the measurement, the type of instrument or method used to make the measurement and numerous other factors. With sufficient time and resources most sources of measurement error can be identified, quantified and corrected for; this is rarely true in practice, however. In general, to cover these "uncertainties" a **mathematical model** is applied that attempts to estimate how close we are to the true measurement. One other advantage of calculating uncertainty is that it can reveal areas in which we can improve measurements as it can ***highlight the source of where inaccuracies are occurring***.

There are a number of ways uncertainty can be determined but one of the most widely used, and which is accepted by accreditation bodies, is the **GUM** method published by ISO and the JCGM as "Guide to the Expression of Uncertainty".

In the GUM method there are two approaches to estimating uncertainty using 'Type A' and 'Type B' evaluations.

- *Type A evaluations* - uncertainty estimates using statistics (usually from repeated readings).
- *Type B evaluations* - uncertainty estimates from any other information. This could be information from experience of the measurements, from calibration certificates, manufacturer's specifications, from calculations, from published information, and from common sense.

In most measurement situations, uncertainty evaluations of both types are needed.

Following a step-by-step process (see *Table A2.1*) the calculated uncertainty, $\mathbf{u}_C$, can be determined. This value can be considered to cover one standard deviation from the mean measurement value. However, we may wish to have an overall uncertainty stated at another level of confidence, e.g. 95 percent. This *expanded uncertainty* is determined by multiplying $\mathbf{u}_C$ with a coverage factor *k* (and for normally distributed measurements this is generally 2).

Table A2.1 Steps required for uncertainty calculations.

Step	Action
1	Decide what information is needed from the measurements. Decide what actual measurements and calculations are needed to produce the final result.
2	Carry out the measurements needed.
3	Estimate the uncertainty of each input quantity that feeds into the final result. Express all uncertainties in similar terms
4	Decide whether the errors of the input quantities are independent of each other. If not then some extra calculations or information are needed.
5	Calculate the result of the measurement (including any known corrections for things such as calibration).
6	Determine the combined standard uncertainty from all the individual aspects.
7	Express the uncertainty in terms of a coverage factor (k), together with a size of the uncertainty interval, and state a level of confidence.
8	Write down the measurement result and the uncertainty, and state how they were obtained.

By completing the 8 steps described above information can be gained on the uncertainty present in any measurement made.
Table adapted from Bell's Guide to Uncertainty: http://www.npl.co.uk/upload/pdf/basics-of-uncertainty-activity.pdf

The output of the uncertainty calculations (for example as reported on a certificate form) is given in the equation:

$Y = y \pm U$

Where Y is the output measurement value, y is the measured value and U is the calculate uncertainty - and this is given as **no more** than two significant numbers. This adjustment to the measurement indicates upper and lower bounds where the 'true' value is expected to lie, with a *particular probability*.

References

References

Due to the large number of sources used to generate MiS ver4 it is not possible to list them all in this booklet. However, some selected sources are listed below.

Guides and publications

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2. Defining and Measuring Nature, "Measurement in Antiquity", Jeffrey Huw Williams, 2014.

3. BIPM SI brochure: https://www.bipm.org/en/publications/si-brochure

4. "The CODATA 2017 values of *h, e, k*, and N_A for the revision of the SI", Newell *et al*, 2018.

5. BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP, and OIML. **International vocabulary of metrology** | Basic and general concepts and associated terms (VIM). Joint Committee for Guides in Metrology, JCGM 200:2012. (3rd edition). URL: https://www.bipm.org/documents/20126/2071204/JCGM_200_2012.pdf/f0e1ad45-d337-bbeb-53a6-15fe649d0ff1.

6. "The Beginner's Guide to Uncertainty of Measurement", Good Practice Guide No. 11, Stephanie Bell, National Physical Laboratory.

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8. "Benefit of Legal Metrology for the Economy and Society" John Birch 2004.

9. BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP, and OIML. Evaluation of measurement data | **Guide to the expression of uncertainty in measurement**. Joint Committee for Guides in Metrology, JCGM 100:2008. URL: https://www.bipm.org/documents/20126/2071204/JCGM_100_2008_E.pdf/cb0ef43f-baa5-11cf-3f85-4dcd86f77bd6.

Resource Webpages

Bureau International des Poids et Mesures (BIPM): https://www.bipm.org/en

European Association of National Metrology Institutes: https://www.euramet.org/

European Commission: https://ec.europa.eu/commission/index_en

International Organization of Legal Metrology: https://www.oiml.org/en

National Metrology Systems: bipm-oiml-d1-global.pdf or https://www.oiml.org/en/about/policy-and-legislation/pdf/bipm-oiml-d1-global.pdf

Acknowledgements

Figure 2.1. Geographical location of the Regional Metrological Organisations (RMOs), image courtesy of the BIPM.

Figure 3.1. Traceability and uncertainty in the Hierarchy of standards was adapted from "A Beginner's Guide to Measurement" by Mike Goldsmith. The SI international standard is the Mark II Kibble balance (courtesy Ian Robinson, NPL) and the National standard is NPL's kilogram 18 artifact (courtesy of Stuart Davidson, NPL).

Figure 3.2. Interlaboratory comparisons and accreditation allow the international equivalence of measurements, adapted from EURAMET talk by W. Schmid 2009 https://slideplayer.com/slide/10365761/

Figure 4.2. Examples of various CE marks to show measurement device conformity, adapted from WELMEC guide 8.21, 2012.https://www.welmec.org/welmec/documents/guides/8.21/WELMEC_Guide_8.21-issue-1_Living_guide.pdf

Table A2.1. Steps required for uncertainty calculations, adapted from: "The Beginner's Guide to Uncertainty of Measurement" (GPG11) by Stephanie Bell: https://www.npl.co.uk/gpgs/beginners-guide-measurement-uncertainty-gpg11

Appendix tables A1.1 – A.1.4 on SI units adapted from the BIPM SI brochure: https://www.bipm.org/documents/20126/41483022/SI-Brochure-9-EN.pdf

EURAMET e.V.
Bundesallee 100
38116 Braunschweig
Germany

Phone: +49 531 592 1960
Fax: +49 531 592 1969
E-mail: secretariat@euramet.org

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