The development of modern metrology and its role today

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Modern metrology is the result of more than 200 years of development that began with the creation of the decimal metric system at the time of the French Revolution and the beginning, at about the same time, of mass production using interchangeable parts. This article traces these developments and describes how world metrology is organized today and gives examples of applications of metrology showing how it concerns us all in many aspects of our daily life.

Keywords: metrology; SI; Metre Convention; measurement standards

Now for experience, because we must start from experience, we have none at all or very little of value: no research has been made to assemble particular observations, sufficient in number, either in quality or certitude upon which to base understanding or in some way pertinent. On the contrary, men of science, but at the same time without rigour and with little care, have constructed their philosophical systems on vague rumours or apparent experiments and have attributed to them the weight of law

Francis Bacon Novum Organum 1620

1. Introduction

The origin of today’s metrology can be traced to two events that took place over a period straddling the end of the eighteenth and beginning of the nineteenth centuries: the first was the creation and implementation of the decimal metric system in France; the second was the development of mass production using interchangeable parts. At the time these two events were not linked, although there is strong evidence that the latter also had its beginnings in France. Nevertheless, the metric system was not created in order to facilitate the production of engineered products and the early development of mass production did not in any way rely upon the new units of measurement. The origins of the metric system sprang first from attempts to unify and bring some order to the confusion created by the multitude of units used in France in local trade, and then embrace the grand idea of producing a set of units that were in some way

One contribution of 14 to a Discussion Meeting ‘The fundamental constants of physics, precision measurements and the base units of the SI’.
natural or fundamental and unrelated to material objects. The development of mass production, on the other hand, was related to the need to produce as many guns as possible in the shortest time and to man’s innate urge to maximize profits in so doing.

As we shall see, however, over the past two centuries these two disparate threads have come together. We can now expand the meaning of the term ‘interchangeable parts’ to encompass not only the real interchangeability of components of high-technology manufacturing, but also the worldwide comparability of a great diversity of measurements made in almost all aspects of our daily life. All of these now depend upon a system of measurement that is itself worldwide and based upon a set of units that can be assured to be universal and constant in time, i.e. as far as possible based on the fundamental constants of nature. There is a third thread that I shall also mention, different from the first two but closely linked to them both, This is the role of metrology in demonstrating conformity to written standards or specifications. This also began at the end of the eighteenth century when fatal explosions of steam boilers led to the drawing up of the first industrial safety standards. It has also expanded enormously and of the multitude of written standards in the voluntary and regulated sectors that exist today, the large majority call upon measurements of one sort or another to demonstrate that they have been met, i.e. metrology is an essential component.

As is well known, the metric system took some time to become established in France; people everywhere have a natural resistance to change, particularly in respect of such basic things as the units in which they transact their everyday business. It was not until 1840 that the metric system in France became the sole legal system of measurement, although by that time it had been taken up in a number of other European countries. For example, it became legal in the Netherlands in 1820. Despite early interest by Sir John Riggs Miller, a British Member of Parliament in the 1780s and Thomas Jefferson at that time American Minister to France, neither Great Britain nor America adopted the metric system at the end of the eighteenth century. The American Congress took little notice of Jefferson’s proposals when he was Secretary of State to George Washington in the early 1790s, and the British Parliament let the matter drop when Riggs Miller lost his seat at a by-election. Britain went on to bring in a new weights and measures law defining new standards of the yard and the imperial pound in 1824. There were, however, serious attempts to introduce the metric system in Britain and the British Empire during the first decade of the twentieth century. Despite strong support from most of the colonies and many quarters in England these failed, ultimately because of the strong opposition of certain manufacturing trades opposed to the heavy financial costs of changing patterns, drawings and machine tools. In other words, the proposals had in one sense come too late. By that time manufacturing industries had become completely locked into the national standards—the key one being of course length, with the inch as the reference for all engineering tools and designs.

The development of mass production of engineered goods seems to have started in France in 1778 when Honoré Blanc, the superintendent of the Royal Ordnance factory at St. Etienne, attempted to introduce a system of production based on pre-constructed filing jigs that could be used by unskilled labour to produce precision parts for the flint-locks of muskets. A hierarchy of standard
jigs was established and particular care was attached to the accuracy of the screws and nuts. He managed to produce some 200 locks made from interchangeable parts. Overall, however, the attempt to extend this to other plants failed and the whole enterprise was abandoned due to opposition from skilled workers who saw their livelihood threatened. The credit for the successful implementation of the first mass production using interchangeable parts is usually given, however, to Eli Whitney who obtained a contract from the American government in 1798 to produce 10,000 muskets within a period of 2 years. Although he failed to meet the delivery date (by some 10 years) and the interchangeability of the parts was limited, it marked the beginning of large-scale manufacture in the USA not only of muskets but also of other manufactured goods progressively adapted to the principle of interchangeability of parts. The need very quickly appeared for local standards and a well-established hierarchy of references in each factory.

The rapid development of manufacturing technology during the first half of the nineteenth century was accompanied by, and in fact could hardly have taken place without, a corresponding development in the design and manufacture of measuring machines, standardization of screw threads and indeed such basic things as engineering flat surfaces and straight edges, all of which are essential for precision manufacturing on a large scale. Among the famous names involved were Henry Maudsley, who made what is probably the first accurate measuring machine, which he called his Lord Chancellor (now in the Science Museum, London) and Joseph Whitworth, who was trained by Maudsley. Whitworth is credited with developing, while working for Maudsley, the technique of making a flat surface by successively scraping off the high spots from three flats one against each other. In due course, Whitworth was able to make steel plates sufficiently flat that they would stick together. He then went on to produce many measuring machines and introduced his system of standard screw threads. By the middle of the nineteenth century engineering metrology had reached a high level with widely available measuring machines that could measure to 0.0001 inch with corresponding flat surfaces and straight edges also at the disposal of engineering works. Added to these was the codification of the principles of engineering design that allowed rigid structures to be made with well-fitting components connected together so that linear and circular movements could be obtained. All of this comes under the name of kinematic design. In the 1840s, the principles of engineering design were even beginning to be taught at Cambridge University by Robert Willis who is thought to have been the person from whom James Clark Maxwell and William Thomson learnt their principles of mechanisms and engineering design.

The next major advance in engineering metrology was made by Carl Eduard Johansson, who in the last decade of the nineteenth century invented the techniques for making accurate gauge blocks by hand lapping using a domestic sewing machine. He made sets of 102 gauges each having an accuracy of 1 μm. Standards of length in the range from 1 to 201 mm with an accuracy better than 10 μm could be obtained by wringing together combinations of two or more individual gauges.

The stage was thus set for the development of modern metrology.
2. The Metre Convention of 1875 and the creation of the first national standards laboratories

While all these advances were being made in engineering metrology and industrial production, there had been no changes in the standards of length and mass established at the time of the French Revolution. Moves towards a formal international adoption of the metric system did not emerge until the middle of the nineteenth century. The Great Exhibition of 1851 held in London was the first of the Great Exhibitions that took place during the second-half of the nineteenth century bringing together manufactured products from all over the world. At the 1851 Exhibition, the great advances made in mechanical engineering particularly in Britain and in mass production notably (by that time) in the USA were evident for all to see. Joseph Whitworth exhibited his ‘millionth’ machine, a measuring machine purporting to be able to measure to one millionth of an inch. It was clear that although great advances were being made, there was still a great disparity in units of measurements, not just in length and mass but in many other areas as well.

At the 1855 Exhibition held in Paris, formal moves began with a view to establishing a worldwide agreement on units of measurement based on the decimal metric system. The Commissaires and members of the jury judging the exhibits, led by Professor Leone Levi FRS made a formal request at the closure of the Exhibition to Governments there represented for the establishment of a worldwide system of weights and measures based on the decimal metric system. This was supported at about the same time by a request from the Society of Arts and Manufacturing in London to the Treasury for the introduction of the metric system in Britain and the Empire. At the first international statistical Congress held in Paris also in 1855, James Yates FRS proposed the creation of an international association for the adoption of the metric system. In 1864, the use of the metric system became legal in Britain and in 1868 it was adopted in Germany.

At the Great Exhibition held in Paris in 1867, a Committee for Weights and Measures and Money was formed. In the same year, two other important calls for action were made. The first was from the Academy of Science of Saint Petersburg and the second from the newly formed International Association for Geodesy, both requesting government action to establish a common system of weights and measures. The French Bureau de Longitude transmitted both of these requests to the French Government and then with representatives of the Academy of Science of Paris and later the Academy of Saint Petersburg made a formal request to the French Government for the creation of an international commission to oversee the construction of new international metric standards with a view to thereby making the metric system truly international. The British delegate to these discussions was the Astronomer Royal Sir George Airy FRS.

Such an international Commission, that included Airy, was created in 1870 by the French Government and the result, after some years of often hard discussions, was a diplomatic Conference in Paris in 1875 at which it was proposed to create an International Bureau of Weights and Measures, where the new international prototypes of the metre and kilogram would be deposited for the use of all member governments of the proposed Metre Convention. At the Conference there was a strong division of opinion between those who considered
that the new international Bureau should be a scientific organization charged
with carrying out scientific work related to metrology, led principally by
Professor W. Forster from Germany, and those who considered that it be simply
the depository of the metric prototypes to be made available to representatives of
member governments on request. This difference of opinion reflected very clearly
the different views being expressed in many European countries at the time as to
who should finance and organize scientific research. The enormous growth in
science (almost exclusively in universities or through independent aristocratic
researchers) and its evident consequences for industrial development and
international trade (matters in which governments take a close interest) had
led to many requests for government financial support. On the one hand, the
university researchers who needed money for the increasingly expensive
laboratories did not want government direction and on the other, the
governments, which were almost all liberal and laissez-faire in persuasion, did
not feel the need to spend taxpayers’ money on activities whose immediate
outcome, by their very nature, were unpredictable. The proposed creation of an
international laboratory was considered by some as going too far and that
research on measurement standards could only be carried out in universities free
of government control. In the end, however, the outcome was a large majority in
favour of the new international institute being a scientific one and thus it was
created in 1875. Not too many years later, its fifth director Charles Edouard
Guillaume, was awarded the 1920 Nobel Prize for physics for his discovery
and development of the low thermal expansion alloys of nickel known as Invar and
Elinvar. A full description of the Bureau International des Poids et Measures

Figure 1. The International Organization of the Metre Convention.

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(BIPM) today and the scientific work carried out there is to be found on the BIPM web site (www.bipm.org). Despite the strong support of Sir George Airy during the discussions that led up to the signing of the Convention in 1875, Britain did not sign at that time but only some 9 years later, in 1884.

The organizational structure created by the Convention as it is today is illustrated in figure 1. It comprises a General Conference on Weights and Measures (CGPM) that meets in Paris every 4 years, an International Committee for Weights and Measures (CIPM) made up of 18 individuals and now 10 Consultative Committees charged with giving advice to the CIPM on metrological matters in a wide range of scientific fields. There are now (2005) 51 Member States of the Convention and 17 Associate States and Economies of the CGPM. A large amount of information on the Metre Convention, the CGPM the CIPM and the BIPM is to be found on the BIPM web site.

In 1887, soon after the signing of the Convention, the German government established the Physikalisch-Technische Reichsanstalt (PTR) in Berlin as the first national standards laboratory. This was followed in 1900 by the foundation of the National Physical Laboratory (NPL) in Teddington and the National Bureau of Standards (NBS) in Washington, DC in 1901. The role of governments in metrology thereby became firmly established. Today all industrialized countries of the world, as well most developing countries, have a national institute charged with maintaining and disseminating national standards. These have become known as national metrology institutes (NMIs).

The scientific nature of the work carried out in such an institute was clear from the beginning by the calibre of the staff and directors of these newly created institutes. The first President of the PTR was Helmholtz, the Chairman of the Governing Board was Siemens. In Great Britain, the first Director was Sir Tetley Glazebrook FRS and the Chairman of the Governing Board was Lord Rayleigh. The Royal Society held an important place in the governance of the NPL for many years, relinquishing it only in the 1960s. A number of early British members of the CIPM were Fellows of the Royal Society. They were: W. H. Christie, a member of the CIPM from 1885 to 1891; Sir David Gill, a member from 1907 to 1914 and P. A. MacMahon from 1919 to 1929. All of the Directors of the NPL from the time of Glazebrook up to Sir Gordon Sutherland in the 1960s were also Fellows of the Royal Society.

The range of metrological activity carried out under the auspices of the Metre Convention has greatly expanded since 1875. The first attempts to move beyond the metre and the kilogram and temperature (already necessary for the thermal properties of the metre) were not long in coming. In 1881 at the first international Congress of Electricians that took place in Paris, it was proposed that the Metre Convention should take responsibility for electrical standards. Despite a very large majority of delegates in favour of the proposal, it met with opposition, essentially by those who only 6 years previously had objected to the creation of the BIPM as a scientific organization. The argument was that the BIPM would not be a suitable institution to take part in the very active scientific work then in progress aimed at establishing electrical standards. Despite support from the French government, that went as far as asking for estimates of the cost of the additional buildings that would be required at the BIPM, the proposal to include electrical standards into the Metre Convention at that time failed.
During the first decade of the twentieth century, the British member of the CIPM, Sir David Gill FRS and the then newly appointed Director of the NBS, Samuel Stratton, both made great efforts to enlarge the role of the Metre Convention to include all areas of science where there was a need for international work in metrology. They did not succeed and it was not until the 6th CGPM in 1921 that agreement was reached to include electrical standards. Photometric standards soon followed in 1927 and in the 1960s ionizing radiation standards were added. Although frequency measurements were implicitly included in the Metre Convention, the unit of time being defined by the 11th CGPM in 1960 at the moment it created the International System of Units (SI), responsibility for time standards came to the BIPM only in 1987. Similarly, the mole, unit of amount of substance was defined by the CGPM in 1971, but the responsibility of the BIPM for metrology in chemistry started only in 1993.

Finally, at the 21st General Conference in 1999, the Member States accepted a proposal from the CIPM that the Metre Convention should have authority to take action in any field of science for which there was a need for international work in metrology. This proposal came in a wide-ranging Report on future activities and needs for metrology drawn up by W. R. Blevin, at that time Secretary of the CIPM. As a consequence of this extension of the activities to be carried out under the Convention, the BIPM was instrumental in the creation of a Joint Committee for Traceability in Laboratory Medicine (JCTLM) which brought together the BIPM with the International Federation of Clinical Chemistry and Laboratory Medicine and the International Laboratory Accreditation Cooperation (ILAC) as well as representatives of manufacturers and regulators in the field of clinical chemistry. In order to formalize some of its relations with international bodies having links with metrology, the BIPM has signed memorandums of understanding with several worldwide organizations such as the International Organization for Legal Metrology, ILAC, the World Meteorological Organization and the World Health Organization. In addition it has active cooperation with several others, as a representative in working groups or commissions.

3. The International System of Units

One of the important products of the work of the CIPM and its Consultative Committees is the International System of Units (SI). Formally adopted by the 11th CGPM in 1960, the SI was the culmination of more than a century of study and discussion on how best to establish a system of units that would bring together mechanical and electrical units. Today, the SI includes the seven base units, derived units made up of algebraic combinations of the base units, multiples and submultiples and rules for their use. All this is laid out in a document approved by the CIPM and published by the BIPM under the title of The SI Brochure. The Brochure, a document of some 75 pages, is now in its 7th edition (1998) and the 8th edition, approved by the CIPM in October 2004, is due to be published in 2005. The full text in French and in English is freely available on the BIPM web site and includes a brief history of the development of ideas during the nineteenth and early twentieth centuries related to units. The SI is indisputably the basis of all aspects of modern metrology.
4. Accuracy rather than simply reproducibility or precision

The question is often posed as to what extent it is necessary to talk about accurate or ‘absolute’ measurement when surely all that is needed is some sort of comparability across the world leading to reproducibility over reasonable periods of time, and surely this can be achieved without any call upon measurements linked to atomic physics or fundamental constants? In other words why is metrology today so complex and expensive? Has it not all already been done? What have you all been doing since the time of Maxwell?

What is not understood by those putting forward these sorts of arguments is that it is only by means of accurate measurements, ones that provide a close representation of nature, that the apparently simple requirement for comparability and long-term reproducibility can be met. Accurate measurements are those made in terms of units firmly linked to fundamental physics so that they are (i) repeatable in the long term and (ii) consistent with measurements made in other areas of science and technology. They are thus much more than merely reproducible or uniform. Measurement standards based upon material artefacts cannot provide the assurance of long-term stability and, indeed, the principal weakness of the SI in this respect is our inability to establish the long-term stability of the kilogram until such time as we will be able to define it in terms of atomic or fundamental physical constants. The precision with which measurements are made depends on the application. The accuracy and the precision must be matched. It serves no useful purpose if the precision is not sufficient even if the accuracy is high, but a precise measurement is not correct if the accuracy does not match the precision.

5. The role of a national metrology institute

The roles of the first NMIs, the PTR, NPL and NBS were quite clear. They were to support national manufacturing industries, to establish national measurement standards, to provide calibrations and, where necessary, to ensure comparability with the national standards of other countries for the purposes of international trade—the most important of all these being the first. Indeed, both the NPL and the NBS were created in part because their governments had been persuaded that the success of the PTR was giving German industry an ‘unfair’ advantage! In those days a clear hierarchical chain existed for almost all measurement standards, extending from the national standard to the workshop bench. Traceability, in the sense of a continuous chain of calibration certificates accompanying material artefacts, soon extended throughout individual nations and across the world through occasional international comparisons of national standards. In this the BIPM played a key role for length and mass, of course.

Up until about the 1970s, most high-level calibrations for industrial clients were carried out by the national laboratories themselves. This then became increasingly difficult as the number of such calibrations outstripped the resources of these laboratories. National calibration services were set-up comprising networks of independent calibration laboratories that obtained their measurement standards from and followed procedures and assured quality of their calibrations under the oversight of the national laboratories. Today, very few
industrial calibrations are carried out directly for industrial clients. The role of the NMI (as it is now called) in this respect is to provide the national standards and disseminate them through calibrations to the national calibration service. This is now almost always a separate organization that has the responsibility of organizing and assuring quality of operation of the calibration laboratories. Despite this separation of responsibilities, the NMI still carries out the essential task of the dissemination of expertise in measurement and calibration. One of the ways this takes place is through the participation of experts from the NMI in the evaluation of the competence of the calibration laboratories. Thus, although the total number of calibration certificates issued by an NMI now is much lower than in the past, each certificate going to a calibration laboratory is the reference for hundreds if not thousands of calibration certificates issued by that calibration laboratory.

In parallel with the creation of independent national calibration services comprising independent calibration laboratories, both national and international bodies have evolved whose task is to accredit these calibration laboratories. At the beginning these accreditation bodies often were part of the NMI, but in many countries they were soon separated from the NMI. Their technical expertise, however, rightly still rests very much on the experts from the NMI who carry out the technical evaluation of the services offered by calibration laboratories. The evolution of the accreditation business has not been without certain difficulties concerning the relation between the national accreditation body and the local NMI. This was addressed in Resolution 11 of the 22nd CGPM in 2003 which is available on the BIPM web site. One might regret that this separation between NMIs and the accreditation bodies has taken place in most countries since the effectiveness of the accreditation of calibration laboratories depends wholly on the technical expertise that can come only from the NMI.

(a) Research, its purpose and benefits in an NMI

Measurement standards are not static. They evolve continually to reflect advances in science and in response to changing industrial and other needs. It is necessary, therefore, for an NMI to maintain an active research base in measurement science, so that the nation can obtain the most advanced and accurate calibrations and the most up-to-date expertise and advice on measurement are available to industry, society and government. Research in measurement science is a long-term activity that must necessarily be done in advance of industrial and other requirements. Today’s research provides the base for tomorrow’s calibration services.

The national benefits of an active research base in an NMI are not only long-term, they are also immediately available through the expertise of the staff that comes only from being active in research. Major NMIs have thousands of industrial visitors each year, they run courses and seminars and are represented on all important industrial standards bodies. These close contacts with national industry also provide some of the essential knowledge for the NMI on present and future industrial requirements and the technology transfer to users in the country.

The advantages to be gained by having all measurement standards in one institute are now widely recognized. A considerable synergy now exists between
the many areas of metrology and an institute that contains them all stands to gain significantly, not only in efficiency, but also in the quality and vibrancy of its science. Many techniques of atomic physics are common to all of these areas. This was foreseen more than 100 years ago by Maxwell during his presidential address to the British Association for the Advancement of Science in 1870:

Yet, after all, the dimensions of our earth and its time of rotation, though, relatively to our present means of comparison, very permanent, are not so by physical necessity. The Earth might contract by cooling, or it might be enlarged by a layer of meteorites falling on it, or its rate of revolution might slowly slacken, and yet it would continue to be as much a planet as before. But a molecule, say of hydrogen, if either its mass or its time of vibration were to be altered in the least, would no longer be a molecule of hydrogen.

If, then we wish to obtain standards of length, time, and mass which shall be absolutely permanent, we must seek them not in the dimensions, or the motion, or the mass of our planet, but in the wavelength, the period of vibration, and the absolute mass of these imperishable and unalterable and perfectly similar molecules.

The establishment of accurate and practical measurement standards linked to fundamental constants, having also the range and diversity required for the whole of modern science and technology, is a major undertaking. Many areas of advanced metrology are now linked directly or indirectly to fundamental or atomic constants using techniques at the frontiers of science; we have atomic clocks using trapped ions or cold atoms or Bose–Einstein condensates, laser wavelength standards, femtosecond spectroscopy, quantum electrical standards, isotope dilution mass spectrometry, ultraviolet spectroscopy, nanometrology, atomic interferometry, and many others all of which require highly trained physicists. The days when standards of length, mass, time and electricity were totally separate and dependent on quite different technologies are now past.

Many of the important measurement activities already mentioned involve metrology in chemistry. For some years, the NMIs have been working to put in place the same sort of measurement infrastructure for chemistry as has existed for more than a century for physics and engineering. The rapidly developing field of biotechnology will also require measurement standards and these are also being established in many national institutes.

An all-encompassing institute that includes metrology in all these areas of science will more readily become well known both nationally and internationally, as well as being regarded as the centre for advice and expertise for all of metrology. Such an institute can also meet one of the key requirements of national industries, namely easy and direct access to a wide range of metrological expertise.

Finally, as regards the staff of an NMI. It is only by having an active and vibrant research activity will it be possible to recruit and keep the high-level staff needed to carry out all of the other activities required of a modern NMI.

(b) National and international activities

National and international representation is one of the important responsibilities of an NMI. As global industrial and trade activities are increasingly regulated at a technical level, metrological requirements play an increasingly important part. Such an example of a new activity is global emissions trading...
under the Kyoto Protocol (see below). A prerequisite for such trading is worldwide agreement related to the measurements of emissions of greenhouse gases. NMIs play a key role in this area where their staff members are experts not only in the science but also in the international technical discussions that provide the basis for agreement on the results of measurements.

Traceability of measurement results means that a given result is obtained in terms of measurement units that are linked by an unbroken chain of calibrations or comparisons to national measurement standards—in practical terms—to SI units. At each link of the chain, the uncertainty of the calibration or comparison must be given. In this way a proper uncertainty of the final measurement in terms of SI units can be given. It is only if the uncertainty has been properly calculated is it possible to estimate the reliability of a measurement and decide whether or not it is suitable for the application in hand. The traceability chain may be long, with many intervening calibrations through a complex hierarchy of standards, or it may be short with just one calibration from the NMI.

In some domains, such as in voltage or laser wavelength standards, it is now common for industrial users to have direct access to atomic- or quantum-based standards of the highest accuracy. For the most demanding users, the former hierarchical system of standards is thus disappearing to be replaced by a system of comparisons, which merely verify that these independent commercial primary standards are operating correctly. The role of the national laboratory is, therefore, to provide the means of making these comparisons and to ensure that its own standards are closely linked with those of other countries, either directly or through the BIPM.

In the last two decades, the burden of tasks has increased to the point where it has become more and more difficult for a given NMI to perform all the research, standard maintenance and necessary improvements. Every effort has been made to avoid unnecessary redundancies and to cooperate in research. For this purpose, Regional Metrology Organisations (RMOs) were created, which include the NMIs of most of the countries of a region, whether or not they are members of the Metre Convention. In Europe, it is EUROMET, created in the late eighties and now six such organizations cover a large part of world. They organize comparisons of standards among their members and increasingly try to coordinate research activities and joint projects. The RMOs have achieved a great deal in raising the awareness of metrology, at the same time encouraging and helping the smaller countries to put their NMIs in place. A recent and ongoing activity of EUROMET is known as iMERA, implementing Metrology in the European Research Area. This is an ambitious project whose long-term aim is a European wide metrology research programme. Since 1999, the RMOs have played a key role in implementing the CIPM MRA that we shall now discuss.

The international comparison of national measurement standards has always been an important activity of the national laboratories but at the beginning of the 1990s it became clear that a more formal and structured approach was becoming necessary. This was in part a consequence of the widespread implementation of quality systems based on ISO standards but also a result of the increasing demands for comparability and mutual recognition of measurements made in different parts of the world.

National and international trade is increasingly governed by agreements signed between pairs of trading nations or, more commonly these days, between

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trading blocks of nations. Included in these trade agreements we now find a requirement for mutual recognition of measurements and tests. This is to avoid double testing, in both exporting and importing countries, and is designed principally to eliminate what are called technical barriers to trade as well as the additional costs. The need for mutual recognition of measurements and tests is having a considerable influence on the way that international metrology is carried out. In October 1999, the directors of the NMIs of 38 industrialized countries signed a mutual recognition arrangement (MRA) for national measurement standards and for calibration certificates issued by NMIs. This MRA was drawn up by the CIPM under the Metre Convention and it will have far-reaching consequences. It goes much further than the informal recognition that existed among the major NMIs up to now. It is, however, one of the consequences of the globalization of trade and will form the technical basis for other wider agreements now required by governments. It has now been signed by the Directors of the NMIs of all the industrialized countries of the world and of an increasing number of developing countries. The CIPM MRA has established a large number (some 500) so-called key comparisons of national measurement standards covering all areas of science on the basis of which the NMIs have formally recognized each others calibration certificates. The results are maintained on the BIPM web site in the BIPM key comparison database. This shows the results of the key comparisons and details of the services for which individual NMIs now have worldwide recognition. There are to date some 16 000 of these. The Consultative Committees of the CIPM and the RMOs play an important role in organizing and carrying out the key comparison and giving formal recognition to the results. The calibration measurement services of the NMIs are evaluated through the procedures of the CIPM MRA by the RMOs. This activity is coordinated by a Joint Committee of the RMOs and the BIPM (called the JCRB), one of whose main tasks is to approve the inclusion of the declared calibration and measurement capabilities of individual NMIs in the BIPM database. The operation of the CIPM MRA is an ongoing and complex undertaking but in today’s world of increasing global trade and trade agreements it is essential.

After more than 100 years of operation, the major NMIs have clearly established their continuing role in national economies and shown that their core tasks of establishing, maintaining, improving and disseminating national measurement standards are as essential now as they were when they were created.

The BIPM, like the NMIs, has considerably expanded the range of its activities and also, like the NMIs, it has maintained its core activity as a scientific institution concerned with metrology. It is well accepted that the success the BIPM in its wider international work stems from the expertise and experience of its staff that is created by it being a scientific institution.

6. Applications of metrology today

The economic success of most manufactured products is critically dependent on how well they are made, a requirement in which measurement plays a key role. Telecommunications, transport and navigation are highly dependent on the most
accurate frequency and time services. Human health and safety depend on reliable measurements in medical diagnosis and therapy. Food and agriculture are closely regulated in terms of the use of pesticides and food additives and it is essential to have reliable means of measuring their presence in the human food chain. Protection of the environment and large-scale studies related to global climate change depend critically on accurate measurements, often extending over long periods of time. These require accurate and stable measurement standards. Physical theory, upon which all of our high-technology activities are based, is reliable only to the extent that its predictions can be tested and verified quantitatively. This calls for measurements of the highest accuracy. It is estimated that between 3 and 6% of GDP in an advanced industrial economy is accounted for by measurement and measurement-related operations.

One might think that for the purposes of international trade high-level metrology needs to be carried out only by the most technologically advanced nations. While there is some truth in this, there are pressing needs for a sound metrological base in all countries including those in development and those in transition. An important aspect of international trade in these latter countries is related to the need to be able to demonstrate that their exported products meet strict sanitary and phyto-sanitary requirements in the importing countries. A recent costly example of the absence of such capability was the refusal of the EU to allow the importation of Lake Victoria fish because of doubts as to its level of pollution. The countries concerned, Kenya, Tanzania and Uganda, lost some 100 million euros during the 2 year ban, which was lifted only after an adequate metrology and testing structure had been put in place on site to test fish before export. A metrology capability is also necessary to verify that imported products meet the required specification. This is not only to avoid costly failures, but also in order to be able to provide the protection of the health and safety of the people of these countries from what might otherwise be second-rate goods refused by countries with the proper means to verify conformity to standards. The establishment of high-technology manufacturing facilities in any country normally calls for a basic infrastructure that includes metrology and this is important for all countries. The absence of such a technological infrastructure is certainly an impediment to inward investment.

(a) Measurement in manufacturing industries

Engineering tolerances, i.e. the amount by which dimensions are permitted to depart from specification, have tightened in practically all industrial production by a factor of three every 10 years since 1960. The result is that production engineers in the large-scale manufacture of automotive and electronic products are now required to work at tolerances previously attempted only in fine, small-scale work. For example, the pistons of car engines now under development are made to a tolerance of about 7 \( \mu \)m, roughly that used for the components of mechanical wristwatches.

There are two reasons for this improvement of precision in manufacturing industries over the past 30 years. The first is that in traditional mechanical engineering, gains in performance and reliability have only been possible through improved precision in manufacture. For example, much of the improvement in car fuel efficiency over the past 25 years has been due to improved manufacturing

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tolerances—the pieces fit together much better than in the past. This is also shown by the disappearance of what used to be known as ‘running in’, when the driver of a new car had to maintain low speeds for the first few hundred or one 1000 km with frequent oil changes to remove the particles produced during this running in process. The second is that many of the new technologies, often based upon the practical applications of recent discoveries in physics, simply do not work at all unless high-precision manufacturing is available. Examples of some of these are the electro-optic industries using lasers and fibre-optics, the manufacture of large-scale, integrated circuits and the commercial production of video disks.

The industrial applications of 10 V Josephson systems highlights some of the unexpected advantages to be gained by having a measurement capability two orders of magnitude in advance of apparent needs. Some major manufacturers of digital multimeters installed systems which provide measurements on the production line with an accuracy at least 100 times better than the final specification of the instruments. In doing this they found two important advantages which justified the expense and effort. First, deviations from mean production specifications were noticed well before they became significant, so corrections could be applied, with the result that 100% of the production is well within specification. Second, final calibrations for linearity and accuracy could be made quickly and efficiently, and no significant error arose from the calibration equipment. The systems thus improved the efficiency of production and the quality of the final product.

It is now possible to fly from London to Australia on a commercial jet with only one stop, or soon non-stop, because the range of such aircraft has increased to more than 15 000 km without refuelling. This is because the efficiency of jet engines has been greatly improved owing to two main advances: (i) the development of materials for the turbine blades that can run at higher temperatures and (ii) the much improved manufacture of the turbine blades to give a nearly optimum shape and surface smoothness. In addition, the electronic management of the engine running has been much improved. The efficiency of any heat engine depends on the ratio of the input/output temperatures, the critical temperature here being that of the gas entering the high-temperature turbine which, in the Rolls-Royce Trent 900 used on the new Airbus 380, is close to 2000 K. As regards the manufacturing tolerances these are now of the order of micrometres with surface roughness less than a micrometre. Engineering metrology using three coordinate measuring machines play a key role in this and in many other high-technology manufacturing systems.

(b) Measurement in navigation and communications

The difference in longitude between any two places on the surface of the Earth is proportional to the difference between the local times at the two places. This was known to Hipparcus in the second century BC, but it was not until the middle of the 18th century AD, when sufficiently accurate sea-going clocks were made by John Harrison, that it became possible to make a useful estimate of longitude in this way. Harrison accomplished the remarkable feat of building, in the period from 1730 to 1760, clocks and watches which neither gained nor lost
more than about 4 min on a voyage from London to the West Indies (about 77°
West of Greenwich). This transformed sea navigation.

Accurate timekeeping remains the key to precise navigation, but the clocks
used are now atomic ones involving a method that is quite different from that
understood by Hipparcus. In 1989, Norman Ramsay received the Nobel Prize for
physics for his key contribution to the development of atomic clocks, which are
now the timekeepers of today’s most precise navigation system, the global
positioning system (GPS). The Nobel Prize in 1997 was awarded to Chu, Cohen-
Tannoudji and Phillips for their work on the production and manipulation of cold
atoms leading to a new generation of cold-atom clocks already more than an
order of magnitude more accurate than the classic caesium beam standards. This
will rapidly lead to even more accurate navigation.

GPS is another example of how improvements in accuracy of measurement can
suddenly lead to completely new industries of enormous magnitude and
potential. GPS was originally designed as a purely military GPS and was fitted
with special coding (selective availability, SA) to ensure that users outside the
US military had a precision more than 10 times worse. It was soon found,
however, that the number of civil users of GPS was growing much more rapidly
than expected. By 1992, the sales of GPS hardware reached 120 million dollars
and the new industry based on GPS, which produces digital maps and associated
navigation systems, had sales approaching 2 billion dollars. By the year 2000, all
of this had increased 10 times and the civil use of GPS had become so important
that on 1 May 2000 the SA was definitively switched off allowing civil users the
same high accuracy of positioning as the US military. It is now clear that such
systems cannot be restricted to military use. Before such satellite navigation
systems can be accepted for civil aviation use, however, it is necessary that there
be back-up systems in place. The Russian system GLONASS is already available
for civil use and a European system, Galileo, will be in place before the end of the
decade.

The technology of accurate time dissemination and the maintenance of
national time-scales to within a few microseconds worldwide, is of considerable
commercial importance in its own right. Calls are constantly being made to
increase the rate of data flow in networks and other telecommunications systems.
In these, one limitation to the speed of operation is jitter in the basic frequency of
interconnected parts of the system. When national networks are connected, it is a
basic requirement that their time and frequency systems fit together without
significant drift or jitter. This is the most demanding industrial requirement for
frequency standards.

(c) Measurements in medical diagnosis and therapy

The impact of measurement on trade, commerce, the manufacture of high-
technology products and fundamental physics touches us all, but it is usually
indirect. Metrology has a much more direct influence on our lives, however, when
it involves medical diagnosis or therapy or when we consume food and drink
whose purity and freedom from contamination with heavy metals or pesticide
residues rely on measurements. The accuracy required in these measurements is
much less than that in many of the examples given earlier in this article.
Nevertheless, the reliability of these measurements related to human health and
safety must be beyond reproach, because errors can kill. The economic impact of measurements related to medical diagnosis and treatment is very large. Most industrialized states spend some 10% of their GDP on health. In the USA, it is closer to 15%. Studies have shown that as much as 30% of the costs of medical care are in measurements and tests related to diagnosis. This represents a very large amount of money and governments are now realizing that more must be done to improve the reliability of such measurements and tests. The European Union’s recent In Vitro Diagnostics Directive will have far-reaching consequences in this area because it requires that all diagnostic kits used and imported into the EU must have a calibration traceable to higher level standards. This is not the case at the moment but the JCTLM (see above) has been set-up to meet this requirement and its actions should lead to significant improvements in patient care.

In medical therapy, permissible errors must not be much greater than the smallest physiological effect that can be detected, usually a few percent. Without considerable care, however, errors very much larger than this can occur. Without the efforts that are already made to assure accuracies of a few percent in radiotherapy at the point of delivery, for example, overdoses or underdoses of a factor of two would be common. This is because the routine production of well-characterized ionizing radiations is difficult: the radiations themselves are invisible and no immediate physical or biological effects are discernible either to the operator or to the patient. In order to assure uncertainties at the delivery stage of a few percent, standards in NMIs must be maintained to a small fraction of 1%, a requirement that entails considerable resources and effort. Similar difficulties exist in ensuring accurate and reliable measurements of the presence of heavy metals or pesticide residues in food and water. In fractional terms, the accuracies required are even lower than in medical diagnosis or therapy, but the measurements are difficult to make and an accuracy of even 50% may be hard to obtain because the total quantity involved is so very small. Nevertheless, properly evaluated accuracies are essential to monitor long-term changes in the quality of our food and in the environment. Without a firmly evaluated accuracy there is no way of knowing whether apparently reproducible results are constant in time. To the question, ‘Is the amount of lead in our drinking water smaller than it was 10 years ago?’ It is not clear that a reliable answer can be given.

Such an inadequacy of present metrology to meet the medical and health requirements raises two major problems:

(i) Metrology in ionizing radiations and biological analysis does not seem to have progressed significantly in the last 20 years. The difficulties are of a fundamental character so that an enormous research effort is needed to find more accurate measuring methods.

(ii) Regulatory bodies set-up excessive requirements related to the presence of certain substances ‘just to be on the safe side’ quoting what has become known as the ‘precautionary principle’, without reference to what is known about their toxicity.

In respect of (ii), a problem that is becoming increasingly common results from the fact that levels at which traces of pollutants can be detected continually falls as more and more sensitive apparatus is developed. In many cases, the most
advanced instruments can detect the presence of substances in molecular quantities. The physiological effect of such low concentrations is, however, often quite unknown but because they can, in principle, be detected their presence is forbidden in regulations and written standards.

(d) Global climate studies

Global climate studies have been under way for many years in an attempt to find out first whether there is clear evidence of climate change and second whether human activities are influencing the climate. There is now a broad consensus that the climate is changing and that the emissions of the so-called greenhouse gases must be having some effect. The Kyoto Agreement on limiting emissions of these gases is slowly starting to be implemented and it is becoming clear that there will be important measurement issues to be faced. The trading of emission quotas, as foreseen in the Kyoto agreement will, as in any other trading activity, require agreement of the trading parties to the measurements of the quantity of emissions traded. There is now considerable activity in the NMIs to prepare for this. In a more general sense, climate studies are based on the combination of data from a wide range of disciplines such as oceanography, solar physics, atmospheric physics, vulcanology, and so on. It is first necessary that the data and measurements in all these areas be made using instruments all calibrated in the same units. It is also evident that in any long-term programme to observe small changes in critical climate parameters, the measurements made at the beginning of the study must be compatible with those made at the end, i.e. the measurement standards used to calibrate them must have long-term stability. An example of such a requirement for long-term stability of standards is in the measurement of changes in the amount of ozone in the upper atmosphere. The aim of these studies is to find out the rate at which the amount of ozone is changing over decades. The measurements are delicate and great efforts have to be made to ensure that measurements are properly linked to standards with a known uncertainty. The consequence of these requirements is that all instruments used in climate studies, in all disciplines, must be calibrated in SI units with a carefully evaluated uncertainty because these are the only units that we can be sure are not drifting with time since they are linked to fundamental and atomic constants.

A basic input parameter to all climate studies is the radiation reaching the Earth from the Sun. A systematic change of only 0.2% would have effects on the Earth’s climate comparable with those now taking place. Accurate measurements of the amount of solar radiation reaching the outer layers of the Earth’s atmosphere (known as the solar constant, about 1.4 kW m$^{-2}$) are not possible from the surface of the Earth due to the variable transmission of the atmosphere. For over thirty years, therefore, measurements have been made by radiometers in space. The accuracy of these radiometers has, unfortunately been barely sufficient and has not been helped by the fact that none of them have ever been returned to earth after their series of measurements have been made. It has thus been necessary to carry out complex manipulations of the data to correct for drifts and differences in sensitivities of successive instruments. While no
significant systematic drift in the Sun’s output has been detected, clearly for the future a more accurate method must be implemented.

7. Metrology and fundamental physics

Einstein suddenly became world famous when in 1919 accurate measurements of the precession of the perihelion of the planet Mercury confirmed one of the predictions of his general theory of relativity. Accurate metrology ever since has been at the frontiers of science in confirming or otherwise the predictions of theory. The quotation at the beginning of this article from Francis Bacon’s *Novum Organum* of 1620 is the first evidence of the beginning of modern science. Not only does Bacon call for experience based on observations but he says that these must be ‘sufficient in number, in quality and certitude’ for them to be used as the basis for our understanding of the natural world.

In modern science, the predictions of theory often call for metrology of the highest accuracy either to set increasingly fine limits on the deviation of observations from theoretical predictions, such as tests of the equivalence principle, or to measure the magnitude of a predicted effect such as the Lens-Thirring frame dragging effect.

An important role is played by accurate measurements of the fundamental and atomic constants. For many years CODATA has produced from time to time a set of Recommended Values of the Fundamental Physical Constants as a service to science. Articles in this issue give a full description of how this is done and how the fundamental constants of physics come from theory. Comparing values of the same constants obtained by experiments from different areas of physics tests the self-consistency of theory. Accurate determinations of constants foster development of advanced measurement techniques as well as providing the basis for invariant and highly reproducible measurement standards. An accurate and self-consistent set of values of the fundamental constants allows computations and analysis throughout science and technology from the calculation of energy levels of atoms and molecules to the determination of important properties of industrial materials and processes. Searches for, and setting limits on, time-variation of the fundamental constants is an important contributor to fundamental theory and the understanding of the universe. To study the question ‘why do the constants have the values they have?’ requires us to know what these values are at the highest levels of accuracy so that if they have particular values or ratios these can be clearly seen. This topic also is discussed in another article in this issue.

It suffices to say here that accurate metrology is and will continue to be an essential contributor to basic science through its role in confirming the predictions of theory and showing up departures from theory. The reliability of all of what has gone before related to manufacturing technology, human health and safety, and climate studies for example, is based upon physical theory that has been tested by experiment, exactly as was foreseen by Francis Bacon.

8. What are the economic benefits of metrology?

What is the cost of maintaining the world’s measurement system and does it provide good value for money? An indication of the amounts spent by the
industrialized nations of the world on the provision of measurement standards and calibration services by the NMI is given by the following figures. In the USA and Japan about 40 p.p.m. of GDP (equivalent to nearly 300 million dollars for the US) is spent annually on these services; fractions of GDP spent in the larger European countries are similar. In some of the rapidly developing countries as much as 100 p.p.m. of GDP is being spent on establishing a measurement infrastructure. The annual cost of the BIPM, about 10 million US dollars, represents on average for the contributing member states of the Metre Convention about 1% of what they spend nationally on metrology. In any particular country, the government can use figures of this sort as a guide but it is clear that in any particular case the government has to balance the conflicting demands from all areas such as health, education, defence, etc.

What has changed, however, in the broad field of metrology over the past 10 years is the extension of the application of advanced metrology into chemistry and biology. The demands of the public for assurance as to the safety of foods, the protection of the environment, forensic use of DNA testing and all the other new areas of metrology mentioned in this article will require increased spending at the national and international level in metrology. This cannot be avoided if the requirements are to be met.

The principal source of funding for metrology in all developed industrialized countries is central government. The management of the measurement system is sometimes in private hands but the base funding is always governmental. For the developing countries and those in transition, metrology is now considered an essential part of the technological infrastructure and therefore finance for establishing a metrology service is available through the funding agencies. Although these funds can be used to start up metrology, provision must be made for the continuous support of the essential metrological services from central government.

In recent years considerable efforts have been made to quantify the benefits from metrology. Such studies have been made in the US (NIST), in the UK (NPL), in Canada (NRC) and in Europe by the European Commission. All show that government spending on the metrological infrastructure of a country gives a high rate of return, i.e. the financial benefits far outweigh the costs. Furthermore, improved metrology in healthcare, for example, brings considerable benefits to human health in addition to the direct savings from the reduction in repeat measurements. It is not possible to give a summary here of these studies but the reader is referred to the original texts most of which are available on web sites referenced at the end of this article.

9. Conclusions

Since the creation of the metric system and the beginning of mass production of engineering products, metrology has developed to become a key component of the technical infrastructure of the modern world. The industrialized nations of the world have put in place and support a worldwide network of laboratories that together provide the technical basis for a multitude of the essential constituents of every day life:

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(i) national and international trade increasingly require demonstrated conformity to written standards and specifications with mutual recognition of measurements and tests, i.e. worldwide traceability of measurement results to the SI;

(ii) the economic success of most manufacturing industries is critically dependent on how well products are made, a requirement in which measurement plays a key role;

(iii) navigation, telecommunications, now becoming an increasingly important part of today’s world, require the most accurate time and frequency standards;

(iv) human health and safety depend on reliable measurements in diagnosis and medical treatment, and in the production and trade in food and food products;

(v) the protection of the environment from the short-term and long-term destructive effects of industrial activity can only be assured on the basis of accurate and reliable measurements;

(vi) global climate studies depend on reliable and consistent data from many disciplines over long periods of time and this can only be assured on the basis of measurement standards linked to fundamental and atomic constants;

(vii) physical theory, upon which all of this rests, is reliable only to the extent that its predictions can be verified quantitatively and this calls for measurements of the highest accuracy

(viii) and finally, metrology has been shown to provide a high rate of return on investment.

The way in which the measurement infrastructure is organized and how it is financed are, of course, matters for individual governments to decide. What is sure, however, is that an advanced industrial economy must have access to measurement standards: the government and industry must have access to advice on measurement matters; there must be experts qualified to represent national interests on international bodies concerned with measurement; and, finally, there must exist the research base in measurement science without which none of this is possible. In developing countries, there must be metrological services to support whatever exports the country relies upon, mainly food and textile products, and to provide the technical basis for the prevention of the importation of dangerous goods.

All of this is assured through the activities of the NMIs working together with the BIPM under the Metre Convention. The Convention has, and continues to provide the formal framework in which worldwide activities in metrology are coordinated and the SI is maintained to provide the essential measurement system for today’s society.

One hundred years ago, far-sighted men clearly understood the link between the economic success of manufacturing industry and access to accurate measurement standards, and the need for research to allow these standards to advance. Since then, the accuracies required, and the range of applications requiring accurate measurement, have increased almost beyond recognition, but the basic arguments for a national measurement infrastructure remain today
exactly as set out by such eminent scientists as Siemens, Galton, Rayleigh, Maxwell and Kelvin.

General bibliography

The BIPM web site: www.bipm.org includes a great deal of information on the Metre Convention, General Conferences on Weights and Measures, the CIPM, its Consultative Committees, the SI and the BIPM. On this same web site there are links to national metrology institutes and Regional Metrology Organizations and the Fundamental constants web site of the NIST. It also contains the texts of the 1998 CIPM Report on Needs for International Metrology by W. R. Blevin and its 2003 update by R. W. Kaarls entitled Evolving needs for metrology in Trade, Industry and Society and the Role of the BIPM. The latter also contains a brief account and references to recent studies of the economic benefits of metrology.