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METROLOGY, ITS ROLE IN TODAY'S WORLD

by

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METROLOGY, ITS ROLE IN TODAY'S WORLD[+]

Summary

Measurement and measurement-related operations are estimated to account for between 3 % and 6 % of the GDP in industrialized nations.

This article sets out to explain why accurate measurements are required, how they are obtained and why the search for ever-increasing accuracy will certainly continue. It presents measurement as an important element in the fabric of industrial society and reviews, in technical and economic terms, the roles national metrology laboratories and measurement systems play in high-technology industries, in health and safety, in the protection of the environment and in basic science.

[+] Revised text of a lecture given in Tokyo on 14 October 1993 to the Japanese Instrument Manufacturers Federation.

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1. Introduction

In today's society there exists a vast, often invisible, infrastructure of services, supplies, transport and communication networks. Their existence is usually taken for granted but their presence and smooth operation are essential for everyday life. Part of this hidden infrastructure is metrology, the science of measurement.

Confidence in measurement enters into our lives in a multitude of ways. It allows high volume goods, such as crude oil or natural gas, to be traded in the secure knowledge that the millions of tons of oil or cubic metres of gas bought and sold are correctly measured from the super-tanker to the petrol pump and from the high-pressure cross-border pipeline to the domestic gas meter. It is a truism that accurate measurements are required for the efficient manufacture of components for such varied things as internal combustion and gas turbine engines, where reliability and long life depend upon manufacturing tolerances of micrometres; and in compact disk players, which incorporate lenses to focus laser light that are made to tolerances below a tenth of a micrometre. In terms of high-technology industrial production, the list of applications requiring accurate measurement is endless.

International telecommunication systems work reliably and efficiently, but for high rates of data transmission time scales across the world must be closely coordinated and must not fluctuate from microsecond to microsecond, from minute to minute or from day to day. Within the industrialized world, national time scales are linked to within about a microsecond to UTC, the international time scale based on atomic clocks. UTC is also the time scale maintained by the atomic clocks (corrected for the effects of general relativity) on board the satellites of the Global Positioning System (GPS), the military and civil worldwide navigation system set up by the US Department of Defence.

The practice of medicine requires careful and sometimes difficult measurement both in diagnosis, as in the measurement of blood cholesterol level, and in therapy, as in the measurement of x-ray or γ-ray dose for the treatment of some forms of cancer. In these measurements reliability is of the utmost importance for errors can, and have been known to, kill.

In agriculture, the testing of food products and the protection of the environment, measurement is becoming increasingly important in providing the basis for, and the means of verifying conformity to, a wide range of legislation. Much of this is related to ensuring that pesticide and heavy-metal residues in food are kept at safe levels.

Individually each of these applications of measurement and the need to have confidence in them is obvious when they are brought to our attention. It is perhaps less obvious that reliable and accurate measurements having long-term stability can only be assured by a measurement system firmly linked to fundamental physics.

The continuous search for greater accuracy in measurement is driven by the increasing demands of high technology for efficiency and performance and its success is made possible by advances in physics which themselves often lead to new technologies. An example of this is the laser. Almost at a stroke, the invention of the laser allowed measurements of optical wavelengths to be made with accuracies some two orders of magnitude higher than was possible before. It also led to the development of instruments and devices, such as the compact disk player, that both incorporate a laser and rely for their manufacture upon the advances in dimensional metrology made possible by the laser.

The fundamental physics upon which all of today's advanced technology is based is itself reliable only to the extent that its predictions can be tested in a quantitative way. The testing of physical theories by the carrying out of increasingly accurate experiments and the establishment of a consistent set of the fundamental physical constants are an essential component of the progress of science and are parts of the activity known as metrology. The provision of reliable and accurate data on the properties of materials is a related activity, and makes an essential contribution to the infrastructure of engineering and high-technology manufacturing.

For the best part of one hundred years, a close network of national metrology laboratories has developed and maintained what is now a worldwide measurement system assuring accuracy and uniformity in measurement standards at both the national and international level. These laboratories carry out long-term basic research on measurement with the aim of advancing the frontiers of measurement science and thereby maintaining their expertise necessary to carry out the function of a national measurement laboratory. Only active involvement in research can give them the competence to carry out high accuracy calibrations of measurement standards, to provide authoritative advice to industry and government and to represent the national interest at the international meetings where binding decisions are taken on measurement and measurement-related questions.

The way in which metrology is organized and the funds assigned to it vary from country to country. Because this activity tends to be both invisible and costly, governments sometimes find difficulty in justifying its support. In those cases where well-established laboratories and national measurement systems exist, operating within a clear framework of national legislation, and where neither the short nor the long-term goals are in question, the problems that arise are those of making the most efficient use of resources. In other cases, where there is no clear understanding in government, or occasionally even in industry, of the role that metrology plays in the industrial and commercial success of the country, the situation is very different. The national laboratory, or whatever organization for metrology exists, is subject to continual review: the need for the work, its basic goals and the means to attain them, as well as every detail of the programme, are permanently in question. Under these circumstances the programme of work is drawn up taking careful account of the costs but with little reference to its value. Only too often the result is that not the government, which pays for the work, nor the industry and commerce that should benefit from it, nor the national laboratory which carries it out, are satisfied or well served.

The aim of this article is to outline the basic justification for government support of metrology by demonstrating its role in national and international affairs and, thereby, to provide some answers to those who ask: what is metrology for?, why does it cost so much?, and why do we keep having to do it?

2. Metrology in trade and commerce : the Convention du Mètre, SI units

The origins of metrology go back to the earliest traders whose instruments of exchange were gold coins and the beam balance. In some respects little has changed since, except that these days the coins are rarely of gold. Then, as now, the buyer and seller of goods had to agree upon the units of exchange. Today, however, we do not worry about fluctuations in the values of, or rates of exchange between, the units of measurement as we still do for values and rates of currency, because we now have an agreed and stable system of units of measurements which is recognized worldwide. This security is based on the Convention du Mètre, signed in Paris in 1875 and maintained ever since by the Bureau International des Poids et Mesures at Sèvres and the national metrology laboratories. The need for such an international convention was first recognized in the 1860s as being one of the essential requirements for the growth of international trade in manufactured and industrial products. The decimal metric system created at the time of the French Revolution was, by the middle of the 19th century, widely used not only in France but also in most European countries. The metric system was thus chosen as the basis for the international system of units created by the Convention which is an intergovernmental treaty between the now forty-seven adhering nations, comprising substantially all of the industrialized nations of the world. The Convention established a permanent organizational structure within which governments can act in common accord on all matters relating to units of measurement. This includes a requirement for periodic Conférences Générales des Poids et Mesures (CGPMs) that now take place once every four years in Paris, and a Comité International des Poids et Mesures (CIPM) whose membership is eighteen individuals elected by the CGPM. The Convention also created the Bureau International des Poids et Mesures (BIPM) which today, with its laboratories and a staff of almost 70 persons, acts as the world centre for metrology.

Soon after the foundation of the BIPM a number of the major trading and industrial nations of the world established their own national laboratories for standards. Among these were the Physikalische-Technische Reichsanstalt, Berlin (1887), the National Physical Laboratory, Teddington (1900), the Bureau of Standards, Washington (1901) and the National Research Laboratory of Metrology, Tokyo (1903). Others soon followed and there now exist metrology laboratories in virtually all of the industrialized nations of the world. These are responsible for providing the national standards of measurement and in many cases for managing the national measurement system comprising calibration laboratories, certification and accreditation bodies, and legal metrology.

The metric system, upon which the Convention du Mètre was based, grew to include electrical and photometric units and in 1960 the modern form of the metric system, the Système International d'Unités (SI), was formally adopted by the 10th CGPM. The SI now has seven base units [1] and includes derived and supplementary units together with prefixes for the multiples and submultiples of the SI units and has established a comprehensive specification for units of measurement. The SI is now the unit system almost universally used for science and technology. Even in the USA, the last bastion of the imperial system, the move to SI continues. It is impossible for it to be otherwise. Measurement is an intimate part of high-technology industry, and most of the world's major companies are now multi-nationals having production plants in more than one country. The continuing use of multiple systems of units leads to reductions in production efficiency and is a source of errors, thus running counter to today's drive for competitiveness and quality.

Before the Convention du Mètre the local, regional and national units of measurement, and their enforcement in law, were maintained by what were generally called Weights and Measures offices. The successors of these offices, usually still under the same name, are now responsible for legal metrology. This is the aspect of metrology directly controlled by law and in most countries concerns those measurements that enter into the buying and selling of goods to the public. Very strict requirements govern such transactions since large quantities of goods and correspondingly large amounts of money are involved. For example, each year in the UK, some thirty billion litres of petrol are sold with a value of some fifteen billion pounds. Overall, about one third of the gross domestic product of Western industrialized countries is in the form of internal retail trade. All of this comes under the purvue of the Weights and Measures offices or their equivalent. These in turn obtain their reference standards for the verification of retail measuring instruments, from the national metrology laboratories. The accuracies with which retail measurements must be made is not generally high compared with the capabilities of the national laboratories. Their reliability, however, must be beyond reproach and the possibilities for fraud, minimized. Public tolerance for false measures is, quite rightly, very low. The error allowed, for example, in the amount of fuel dispensed by a petrol pump, in the UK is normally about ± 0,3 %, but 0,3 % of £ 15 billion is still some £ 50 million !

Similar examples could be given for international trade in such products as crude oil and natural gas where the same principles apply as for internal national trade. The role of metrology in those cases, however, is to provide a secure and accessible base upon which to establish the international legal and regulatory framework.

A much larger role for metrology, and one which extends its capabilities to the limit, is the provision of the accurate measurements required in high-technology manufacturing and telecommunications.

3. Metrology in high technology manufacturing industries

3.1. *Precision of manufacture and performance*

About half of all manufactured products is accounted for by individual items such as aircraft, motor vehicles and computers, together with their component parts. The other half mostly comprises goods manufactured in bulk. In the USA, the value of discrete items amounts to about 600 billion dollars (more than 10 % of GDP). Of this, about half is in the automobile industry [2], other important sectors being aerospace and instrumentation, see Table 1. For most of these products their performance and percieved quality, and hence their commercial success, is determined by how well they are made. Engineering tolerances, i.e., the amount by which dimensions are permitted to depart from specification, have fallen by a factor of three every ten years since 1960, *see* Figure 1. Such a reduction in manufacturing tolerances pre-supposes corresponding improvements in precision machining and in metrology.

There are two reasons for this improvement of precision in manufacturing industries over the past thirty years. The first is that in traditional mechanical engineering improvements in performance and reliability have only been possible through improved precision in manufacture. The second is that many of the new technologies, based upon the practical application of recent discoveries in physics, simply do not work unless high precision manufacturing is available. Examples of some of these, *see* Table 2, are the electro-optic industries using lasers and fibre-optics, the manufacture of large scale integrated circuits, and the commercial production of positioning and navigation systems using signals from atomic clocks on satellites. Dimensional tolerances of 0,1 μm and below, and timing tolerances of a few nanoseconds, are required in the examples given. Such fine tolerances in manufacture and use require an accuracy in measurement capability at an even finer level.

It is now well known that the performance of many manufactured products continues to improve when the mechanical and other errors of manufacture are reduced far beyond what, at first sight, is required. A striking example of this is to be found in gear boxes of the sort used in gas turbines to drive contra-rotating propellers, an engine configuration now considered to be the most efficient for large passenger aircraft [3]. The capacity of the gear box, defined as the torque that can be transmitted per unit weight, increases dramatically as the individual gear-tooth error falls *see* Figure 2. Capacity doubled when the tooth position and form error fell from 10 μm to 3 μm, the best at present available in production. A further doubling of capacity is expected when the overall tooth error is reduced from 3 µm to 1 µm. The measurement of position and form of gear teeth with an accuracy of 1 µm is not yet possible either on the production line or in national metrology laboratories. Lifetimes of such components also increase non-linearly with improved precision of manufacture. The tolerance now set in Japan in the production of pistons for some automobile engines is about 7 µm, similar to that required in the manufacture of mechanical watches !

An example of how quality and commercial success are linked to manufacturing precision may be found in the forces required to open US and Japanese car doors [2]. In the 1980s the forces required to open the doors of Japanese and US cars differed by a factor of three. The origin of the difference was that Japanese cars had a tolerance of 1 mm on door and door assemblies and were therefore easier to open than were American cars where the equivalent tolerance was 2 mm. Ease in the opening of the door is an important factor in the perceived quality of the whole product, and is directly related to precision of manufacture. It had large economic consequences for the US motor industry.

In the manufacture of integrated circuits, the essential component of computers and microprocessors, photolithography is the key technology that allows the production of the millions of individual features present on a typical 22 mm x 15 mm chip. The market for integrated circuits is worth hundreds of billions of dollars worldwide and goes to the manufacturers that can pack the most components on a single chip, *see* Figure 3. It is at present concentrated in a small number of US and Japanese companies. Among the most demanding of all dimensional measurements is in the so-called "step and repeat" machines that manipulate the photolithographic masks used to put down the successive layers that make up the microcircuits. In these machines, which cost between 2 and 3 million US dollars each, and for which the annual world market is upwards of 500, errors in the optical images of the masks is kept below 60 nanometres (10^{-9} m) over dimensions of a few centimetres. In today's most advanced machines, images are formed using ultra-violet light from Kr F excimer lasers at a wavelength of 248 nm. Intense research efforts are being made to allow the use of x-rays or electrons so that even finer resolution, and hence denser packing of components, can be achieved. Associated with the step and repeat machines are high-speed, fully-automated x-y measuring systems for checking the shape and dimensions of photolithographic masks and the finished wafers. These systems have a repeatability over 24 hours of 10 nm in a 200 x 200 mm range and incorporate a wavelength stabilized He-Ne laser and active compensation for thermal and mechanical deformation of the silicon water.

3.2. *Improvements in industrial measurement accuracy*

To achieve high precision measurement in production engineering more is required than a simple upgrading of existing precision methods. Among recent initiatives have been the development of new measuring tools, notably the three-coordinate measuring machine (CMM), the application of computers to the calibration and use of such new machines, and the provision of direct access to the SI unit of length through laser interferometry.

Three-coordinate measuring machines comprise three mutually perpendicular axes of linear measurement and sophisticated computer software to allow accurate and rapid evaluation of the shape and dimensions of complex pieces such as bevelled-tooth gears, crankshafts or turbine blades. Three dimensional systematic-error compensation is obtained by calibration using carefully designed test objects. The accuracies of CMMs calibrated in this way can reach a level of about 2 μm in all three coordinate axes over volumes of about 1 m^3. Their performance, however, is critically dependant on the computer software being free of errors. The checking of this software is the most difficult part of the calibration process.

Displacement measurement using laser interferometers can achieve very high accuracy [4] but great care must be exercised to avoid the class of errors known as Abbe errors. These arise essentially from incorrect alignment, so that the optical displacement measured with the interferometer is proportional to, but not equal to, the displacement of the object. Similar errors can arise if an object is displaced by pushing it against a frictional resistance: unless the direction of the applied force is parallel to and coincident with the net resistance vector, the object experiences a torsion stress and deforms. These considerations are important not only in machine tool design, where they have been well known for a hundred years, but also in the design of systems in which the measurements of displacements and dimensions are at the nanometre level and are well known to the designers of the step and repeat machines. Of itself, extreme sensitivity is not a guarantee of accuracy: proper design practice must also be adopted. One of the important activities of the national laboratories in the new field of nanometrology [5], metrology at the scale of nanometres (10^{-9} m), is the exploration of machine behaviour so that good measurement practice can be developed.

3.3. *Direct access to SI units in manufacturing industry*

Direct access to SI units and to quantum based standards has led to improvements in measurement accuracy in many fields of measurement. The application of optical interferometry, using known wavelengths of light, to dimensional metrology allows accurate measurement standards to be built in to three and two dimensional CMMs so that intrinsic errors are now limited only by the refractive index of air. In electrical metrology 1 volt or 10 volt Josephson-array systems allow voltage measurements to be made with reproducibilities of a few parts in 10^{10}. In time measurement, commercial caesium atomic beam clocks allow time to be measured to accuracies of a few parts in 10^{13}, equivalent to a few nanoseconds per day. The possibility of making such measurements either on the production line, as in the case of the voltage measurements, or in practical commercial applications, as in the case of atomic clocks, could not be envisaged if the practical measurements were linked to national standards by the traditional hierarchical chain of calibrations.

Before direct access to these inherently stable units was available in industrial applications, the hierarchical chain of calibrations was the only way to link metrology in manufacture to national and international standards. Consequently, the accuracy of industrial measurement standards was significantly lower than that of national standards. A factor of three or four in each link in the chain hardly be avoided, so that national standards had to be a factor of ten, and sometimes factors of twenty to fifty, more accurate than industrial requirements. Some of the accuracies now required in high technology manufacture, *see* Table 2, would, if the same scheme applied, call for accuracies in national laboratories well beyond what is presently feasible. For example, the present tolerances of 60 nm in the dimensions of photolithographic masks would, if obtained through a traditional calibration chain, require national dimensional standards of better than 3 nm, a figure which at present is well beyond what is feasible.

In a very real sense, the accurate measurements now needed in certain high technology industries are at the frontiers of metrology, and directly based upon fundamental physics. This new situation is reinforcing the role of national metrology institutes as centres of excellence and expertise in advanced measurement since their advice and services are increasingly called upon by those whose requirements are the most demanding. The practical use of Josephson arrays and atomic clocks for accurate measurement and the development of a full physical understanding of their behaviour was carried out in national metrology laboratories. It was from them that industrial enterprises obtained the basic knowledge that led to commercial applications of these devices. The new field of nanotechnology relies heavily on corresponding research in nanometrology, much of which is being carried out in national metrology institutes.

The industrial application of 1 volt or 10 volt Josephson systems highlights some of the unexpected advantages to be gained by a measurement capability two orders of magnitude in advance of apparent needs. In the commercial production of digital multimeters two parameters are fundamental : linearity and full-scale accuracy. The ability to make measurements on the production line with an accuracy two orders of magnitude better than the final specification of the instruments has at least two important advantages :

- deviations from mean production specifications are noticed well before they become significant and corrections can be applied (This allows 100 % of the production to be well within specification);
- final calibrations for linearity and accuracy can be made quickly and efficiently and no significant error comes from the calibration equipment.

The advantages are thus those of efficiency in production, and quality in the final product. According to the manufacturers now using such systems, these advantages outweigh, by a considerable margin, the extra cost of installing and maintaining the Josephson system.

Although this example is from the field of electrical measurements, it is evident that in most industrial production rapid and accurate measurement systems have similar advantages. Indeed, one of the central concepts of so-called computer-aided flexible manufacturing systems is that accurate measurements made in real time during production allow departures from specification to be corrected before they become significant. Older methods, in which components are manufactured and subsequently tested for conformity to specification with the rejection of a certain fraction of the product, cannot compete with those in which 100 % of the product is within specification. To achieve this, however, measurements taken during manufacture must be made at a level significantly below final tolerance.

3.4. *Application of accurate time measurement*

A different type of requirement for accurate measurement is in systems for global positioning and surveying using time signals from earth satellites. Such systems only become of practical value when the accuracy of the key measurement, in this case time, reaches a certain threshold.

The Global Positioning System (GPS) comprises a constellation of 24 satellites orbiting the earth at an altitude of about 20 000 km. Each has on-board caesium beam atomic clocks and transmits coded time signals that can be picked up by small receivers anywhere on the surface of the earth. The clocks on the satellites are all set to the same time, to within about 30 ns. The principle of GPS positioning calls for the simultaneous observation of four satellites in different parts of the sky and measurement of the apparent time differences between them. The position of the receiver on the ground can be found from these apparent time differences knowing the positions of the satellites at the time the observations were made. The satellites are sufficiently high for atmospheric drag to be negligible and are in siderial orbits so that their positions can easily be programmed into the receiver memory. The accuracy of the satellite position in space must be at least as good as the required position accuracy, namely about 10 m. In practice, the overall accuracy for real-time position determination is not as good as this and is only about 30 m, due principally to the difficulty of making accurate corrections for ionospheric delays in signal propagation. Furthermore, for civil use, an intentional degradation, known as Selective Availability (SA), is introduced by the US Dept. of Defence and the accuracy available in the presence of SA is about 100 m. This is of course perfectly adequate for civil navigation. For surveying and other purposes, for which immediate knowledge of the result is not necessary, or for differential measurements, in which a receiver is also placed at a known reference point, the accuracy can be much greater. Under these conditions GPS can give accuracies of 0,1 m. The cost of setting up and maintaining a system such as GPS is very high: each satellite has a life of about eight years and to complete the constellation of 24 satellites has cost more than $ 10 billion dollars, the second most expensive space programme after the manned landing on the moon. This whole system relies completely on the performance of the clocks.

In addition to the military users of GPS there are many civil users. The commercial applications of worldwide positioning and navigation to an accuracy of even 100 m are very wide and there are now many producers of GPS receiving equipment. It is estimated that in 1992 the sales of GPS hardware reached 120 million dollars and the new industry based on GPS and producing digital maps and associated navigation systems had sales approaching 2 billion dollars. Within a few years civil aviation navigation is sure to be based on GPS. New generations of atomic clocks, having accuracies perhaps two orders of magnitude better than those now available, will undoubtedly lead to corresponding improvements in global positioning and corresponding commercial applications. These new clocks, based upon trapped or cooled atoms or ions, are now under development in national laboratories and are expected to have accuracies of parts in 10^{16}.

The technology of accurate time dissemination and the maintenance of national time scales to within a few microseconds worldwide are of high commercial importance [6], quite apart from their use in positioning. Data networks and other telecommunications systems are under continuous pressure to increase the rate of information flow. One limitation to the speed of operation of such systems is jitter in the basic frequency and phase of interconnected parts of the system. If, as is now often the case, different national networks are connected it is a basic requirement that national time and frequency systems fit together without significant jitter. This is the origin of the growing demand to link national time services to within 100 ns, a factor of ten better than is achieved today.

Quite apart from the technological and commercial applications of GPS for time-scale comparisons and positioning, quite unexpected scientific applications are beginning to appear now that the scientific community has become aware of the full potential of the system. For time-scale comparisons and positioning, the delays introduced to the GPS signals by their passage through the ionosphere must be corrected for. Accurate measurement of these delays, however, can provide information on the atmospheric composition and temperature that are of interest to climatologists. Recent studies [7] have indicated that if the ionospheric delays are measured with an accuracy of about 3 ns, equivalent to 1 m of path, which is already possible, GPS could become a valuable tool for the study of long-term changes in atmospheric water and carbon dioxide content as well as temperature in the upper atmosphere.

A substantial increase in accuracy in the measurement of any important physical quantity almost always leads to unexpected applications in fields quite different from that for which the advance was made.

3.5. *Measurement in the JET equipment*

A further example illustrating the key role of measurement, and one that can easily be costed, is research aimed at producing power from nuclear fusion. The possible commercial production of energy from controlled nuclear fusion depends on the results of large and expensive experimental devices such as JET (Joint European Torus). This device has so far cost about 1000 Mecus of which 10 % has been for the measurement systems. Accurate measurement of the temperature and density of the hot plasma (at about 100 million degrees Celsius) is crucial to the understanding of the various loss mechanisms that impede fusion. It is evident that with so much at stake the measurement process must be fully understood and a proper evaluation of the uncertainties made. Were this not the case, there is a risk either of unwarranted euphoria, with subsequent disappointment, (as has already happened with earlier devices) or of failure to appreciate successes achieved. In this work the cost of poor measurement would be very large and hence the great effort and large amount of money quite rightly being devoted to it.

3.6. *Summary*

This brief outline of some of the industrial requirements for accurate measurement has illustrated: (i) the close links that now exist between measurement capability and the efficiency and reliability of industrial products and (ii) the existence of new industries and technologies that have grown up simply because certain high accuracy measurements have become possible on a routine basis. Moreover, in some industries, notably the production of microcircuits, commercial viability in a world market worth many billions of dollars, is dependent on fabrication processes at the frontiers of science calling for the most advanced measurement capabilities. In all of these, the pressure to improve measurement capability will continue because economic success may be seen to flow from such improvements. The ability to make accurate measurements will thus continue to be one of the characteristics of successful high technology industries [8].

4. The need for accuracy rather than simply reproducibility or uniformity in measurement

In describing commercial, industrial applications of measurement I have so far used the words 'precision', 'reproducibility' and 'accuracy' without distinguishing them or giving definitions.

The need for what is sometimes called 'absolute accuracy' is often questioned on the grounds that the actual requirement in most practical situations is that measurements be reproducible and uniform from place to place. The difference between reproducible or uniform measurements on the one hand and accurate measurements on the other is, however, crucial. An accurate measurement is a measurement made in terms of units linked to fundamental physics so that it is (i) repeatable in the long term and (ii) consistent with measurements made in other areas of science or technology. In examining what is done with the most precise measurements it is rarely possible to escape from one or other of these requirements. Thus measurements must be accurate if they are to be really useful and reliable.

A physical or chemical property of a material or substance is quantified by representing it in terms of a unit multiplied by a number. The yield strength of a particular alloy, for example, is a physical quantity whose magnitude may be given by multiplying the unit, in this case the megapascal (MPa), by the number 800 to give 800 MPa ; similarly the mass concentration of lead in drinking water may be given as 20 ng m^{-3}. To assign these quantitative descriptions to physical properties or phenomena irrespective of whether or not the highest accuracy is required, suitable units must be defined and ways found to establish the number by which they must be multiplied.

In choosing units, the requirement for long-term stability at the highest level of accuracy leads directly to units linked through physical theory to atomic or quantum phenomena or fundamental physical constants, as these are the only ones whose immutability is sure. This was recognized more than a century ago by Maxwell who wrote in 1870 : "If 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 unalterable, and perfectly similar molecules." At that time neither physics nor technology had advanced sufficiently for it to be either feasible or necessary for units to be defined in this way although with the work of Michelson, a few years later, it would have been technically possible to define the metre in terms of the wavelength of light. The existing definition, however, was perfectly satisfactory in practice and there was no strong need from the users to move to a more precise definition until much later.

Consistency of measurements across all areas of science is necessary for the practical application of the equations of physics. For this, the starting point can be obtained only by having a system of quantities and units that is itself consistent. At present, consistency is provided by the Système International d'Unités (SI) with its seven base units, derived units, multiples and sub-multiples. Among the SI base units, only the kilogram is defined in terms of a material artefact. The second is explicitly defined in terms of an atomic or quantum phenomenon; the metre in terms of the speed of light and the second; the ampere in terms of a mechanical force and a distance; the kelvin in terms of a thermodynamic equilibrium state; the candela in terms of a power and an arbitrary physiological conversion factor and, finally, the mole is defined in terms of an unspecified number of entities equal to the number of atoms in 12 g of ^{12}C. The ensemble of SI base units is linked through physical theory to atomic and quantum phenomena, and to fundamental physical constants through a complex web of experimental measurements. It thus very largely meets the requirements laid out by Maxwell.

When the equations of physics or engineering are used to calculate, for example, the maximum load that an aircraft wing strut will support, it is assumed not only that the results of the calculations are consistent with those done elsewhere or at another time but also that they represent the behaviour of real wing struts under the real loads foreseen. These assumptions are justified only if calculations are based on equations that correctly model physical systems and on data that correctly represent the properties of the alloy from which the strut is made, i.e. on accurate data.

Data that is reproducible but not accurate can misrepresent nature in a multitude of ways. What is sure, is that it would be unwise to build aircraft designed on the basis of reproducible but not accurate data as they could not be given any guarantee of safety. Likewise chemical analyses of trace amounts of heavy metals in drinking water that are reproducible but significantly in error can result in damage to human health, and they provide no proper basis for long-term control of water quality.

Without a firm basis in 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 ten years ago ? no reliable answer is possible. This leads directly to the subject of the next section.

5. Metrology in human health and safety and in the protection of the environment, metrology in chemical analysis

I have already discussed the impact of measurement in its role in trade, commerce and the manufacture of high-technology products. In these areas, measurement is a key ingredient, and poor measurements lead directly to trade disputes, to inefficient production and to unreliable manufactured products. For many of us, however, measurements have a much more direct influence on our lives when they are part of medical diagnosis or therapy. For better or for worse, medical diagnoses are increasingly made on the basis of the results of measurements. These describe blood pressure, electrical activity of the heart, cholesterol concentration or the levels of many other essential components of the blood. The importance of these measurements is obvious, as is the need for reliability. It is also obvious that accuracies expressed in parts per million are not required. Rather, it is necessary to be sure that errors are not much greater than the smallest detectable physiological effect, usually a few percent. Without considerable care, errors much greater than this can easily occur. The fact that the accuracies sought are not very high, should not disguise the formidable difficulties that must be overcome to achieve these accuracies. Without the efforts that are already made to assure accuracies of a few percent in radio-therapy, for example, overdoses or underdoses of a factor of ten (i.e. about one hundred times the present tolerance) 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 discernable either to the operator or to the patient.

In addition to its role in medicine, measurement is increasingly important in agriculture, in the testing of food products, and in monitoring the environment. Much of this relatively new activity is a consequence of the European Single Market. European Directives (i.e. regulations) on product quality now cover a vast range of products and apply in all countries of the European Union (EU). One of the provisions of the Single Market is that analytical results and tests made by a properly certified and accredited laboratory in one EU country must be accepted in all the others. In preparation for this, the Community Reference Bureau (BCR) has, for a number of years, been carrying on a programme to evaluate the comparability of measurements in different countries and has sought means to improve them. This programme highlighted gross differences in the results of chemical analyses made in different EU countries and was instrumental in bringing about significant improvements.

In many areas, particularly medicine, agriculture and food products, chemical and biochemical analyses were carried out, prior to the BCR work, within closed national systems. Very few cross-border comparisons of these measurements were made because there were no statutory requirements to do so. Astonishing results were obtained when such international comparisons began. One example concerns the determination of aflatoxin B_1 in cattle feed, introduced through peanuts. The permitted levels (EEC Directive 74/63 EEC) are very low, not more than 10 $\mu g\ kg^{-1}$ in compound feed, because aflatoxin reappears as a metabolite (aflatoxin M_1) in milk. This aflatoxin is restricted in milk for infants and some EU countries apply limits of 0,01 $\mu g\ l^{-1}$. The early comparisons organized by the BCR show results which differ by a factor of one thousand between countries. Similar differences were found in determinations of trace amounts of heavy metals (such as Cd, Pb, Hg) in milk powder. In each case, the preparation of stable reference materials and the introduction of standardized analytical methods greatly improved the situation. The initial poor results, however, are typical of what can happen when trace amounts of one substance in another are analyzed in the absence of a common framework for comparisons.

Despite a superficial simplicity, the problem of making accurate trace analyses is a very difficult one. Difficulties arise because the magnitude of the signal representing the trace substance measured depends on a combination of (i) the real amount of the substance present, (ii) the properties of trace amounts of other substances and (iii) the properties of the substance, known as the matrix, which forms the bulk of the sample. Thus, a real amount of 0,01 $\mu g\ l^{-1}$ of aflatoxin M_1 in milk could appear on analysis to be quite different depending upon what other trace substances were present and whether the analytical instrument being used had been correctly calibrated against a comparable sample.

Although the problem of achieving accurate trace analysis has been well known for a long time powerful commercial pressures now demand international traceability, and hence accuracy. Their origin is the need to demonstrate conformity with regulations relating to the sale of food and other products. Similar pressure from governments calls for reliability in measurements used as the basis for national legislation and for international agreements dealing with the protection of the local and global environment. In this case it is a question of balancing the economic costs of restricting or changing industrial activity against the environmental penalties of not doing so. The results of measurements are often crucial in coming to a decision.

The importance of improving the accuracy of measurements in analytical chemistry has led the Comité International des Poids et Mesures to establish a new consultative commitee to advise it on these matters. International comparisons have already begun at the highest level of accuracy with a view to improving the traceability of such measurements to SI. As was the case for physical and engineering measurements at the end of the 19th century, so now towards the end of the 20th century the requirements of international trade present imperative demands for accuracy and international traceability in measurements in analytical chemistry.

6. Metrology and fundamental physics

6.1. *Testing of physical theory*

Confidence in the predictions of physical theory is at the basis of all of today's advanced technology. This confidence exists because the predictions of theory are tested by experiment and theories are rejected, revised or provisionally accepted depending upon the results of the tests. Testing by experiment is a characteristic of modern science which we owe principally to Francis Bacon. It was he who insisted upon the need to carry out real experiments instead of performing the so-called 'thought experiments', which had been used since the time of Aristotle to prove or disprove theories. These 'thought experiments' were no more than descriptions of situations in which the apparently logical consequences of preconcieved views of the world were demonstrated. Very little that was new could be discovered, and much that was false was supposedly proved. Bacon showed that it is possible to devise real experiments that can rebut the predictions of theory and so provide a system of choice between one theory and another. The ability to carry out such crucial experiments soon required the ability to make quantitative measurements. In this way the science of measurement became an essential component in the growth of experimental science from its earliest days and it continues to be so today.

The predictions of two of the most fundamental theories of modern physics, quantum electrodynamics (QED) and general relativity (GR), are still being tested to establish the limits of their applicability and, in the case of general relativity at least, to distinguish them from those of competing theories. By their very nature, the testing of the predictions of both of these theories requires careful and difficult measurements. In the case of QED this is because it deals with the microscopic world of atoms and nuclei, and in the case of GR because in the local universe, the only one to which we have easy access, the differences between the predictions of GR and those of Newtonian physics are extremely small.

To test QED, one experiment consists of making measurements of the anomalous magnetic moment of the electron so that the results can be compared with the value that is predicted by calculation directly from QED. At present the value obtained from the best measurements differs by less than its experimental uncertainty, a few parts in 10^9, from the calculated value.

To test GR is more difficult. Until the beginning of space flight in the 1970s, GR was a domain of theoretical physics almost wholly disconnected from the rest of physics and with no immediate practical application. This has all changed. Any yachtsman who uses a GPS receiver to fix a position at sea depends on corrections for the curvature of space-time that are applied to the rates of the atomic clocks on board the GPS satellites, in orbit 20 000 km above. With the accuracy of present day commercial atomic clocks, a few parts in 10^{13} per day, the equations of GR are relatively straightforward to apply. This will not be the case when the next generation of atomic clocks, having accuracies two or three orders of magnitude better than the present ones, becomes available. Who would have thought only twenty years ago that GR would become a routine part of space engineering and that equipment on sale to the general public would make use of satellite-signals corrected for the curvature of space-time !

On a much more down to earth level, discoveries in solid state physics such as the Josephson or quantum-Hall effects make startling and simple predictions concerning the properties of semi-conductors at low temperatures. That the Josephson voltage is exactly proportional to integral steps of $2e/h$ or that the quantum-Hall resistance is exactly proportional to integral steps of h/e^2 (where e is the charge on the electron and h is Planck's constant) merited the discoverers of these effects their Nobel Prizes, but their predictions have been subject to the most exacting measurements to test whether or not they are universally valid. These and similar discoveries in solid state physics are part of the essential basis of the science upon which today's micro-electronics industries are built.

6.2. *The fundamental physical constants*

So far great emphasis has been placed on the importance of measurement standards being linked through the theories of physics to atomic or quantum phenomena, or to fundamental physical constants, so that they can be assured of long-term stability. What are these so-called fundamental physical constants? The theories of science point to the existence of constants of nature and to certain invariant relations that exist between them. These constants appear quite independently in different areas of science. The fact that they take the same value no matter what type of phenomenon is being considered, indicates that they are of a very fundamental nature and hence their name 'the fundamental physical constants'. A list of the principal fundamental constants [9] is given in Table 3.

Some of these constants appear directly from theory. These include the speed of light c in Einstein's Special Theory of Relativity, the Planck constant h in quantum theory and the Sommerfeld fine structure constant α in QED. Others are properties of the elementary particles, such as the mass m_e and charge e of the electron or the mass m_p and magnetic moment μ_p of the proton. In a third category are those constants that are, in effect, conversion factors between different types of quantities. Among these are the Boltzmann constant k, which is the link between thermal and mechanical energy, and the Avogadro constant N_A, which relates microscopic to macroscopic amounts of matter.

The values of the fundamental constants are obtained in SI units either directly from experiments, as is the case of the magnetic moment of the proton and the Boltzmann constant, or indirectly by calculation, using one of the many relationships that exist between the constants. The universal nature of these constants allows relationships to be found between them that span wide areas of science and are susceptible to experimental test in diverse ways. Indeed, to obtain good agreement between the measured values of these constants obtained using methods based upon quite different areas of physics is one of the ways of confirming the consistency of physical theory and is an important activity in metrology.

Accurate measurements of the fundamental physical constants contribute to advances in physics and to metrology, and are essential, in the long term, to both [10]. The most recent example of the symbiotic relation between metrology physics and high technology industry is to be found in the quantum-Hall effect discovered in 1980. As a practical standard of electrical resistance, the quantum-Hall effect is widely used in national metrology laboratories and even in some industrial companies. The technology developed to use the quantum-Hall effect for metrology, based upon that used in commercial microcircuits, has at the same time been used in accurate experiments to study the physics of a two-dimensional electron gas in GaAs heterostructures. This has turned out to be a very complex phenomenon and much remains to be understood, but it has opened up new avenues of research in physics which, in their turn, will lead to new applications in semiconductor electronics.

7. The role of national metrology laboratories, national measurements systems and regional metrology organizations

Practical application of the SI, for the overwhelming majority of users of measuring equipment who do not themselves have the means for the direct realization of the SI units, is through a national measurement system based upon units maintained or realized in a national metrology laboratory.

7.1. *The origins of national metrology laboratories*

Towards the end of the 19th century, the needs of industry for accurate measurement standards and of international trade for worldwide agreement of measurement standards led to the Convention du Mètre and the foundation of the major national standards laboratories. The objectives of these first national standard laboratories were quite clear. They were to support national manufacturing industry, to establish national measurement standards, to provide calibrations and to ensure comparability with the national standards of other countries. In those days there existed, for almost all measurement standards, a clear hierarchical chain extending from the national standard to the workshop bench. Traceability, in the sense of a continuous chain of calibration certificates, soon extended throughout individual nations and then across the world through international comparisons of national standards.

From the earliest days of the national laboratories until the early 1970s, most high level calibrations for industrial clients were carried out in the national laboratories themselves. This is no longer the case. The number of such calibrations has outgrown the capacity of national laboratories and most calibrations for industry are now carried out in national networks of certified or accredited calibration laboratories. This change has taken place for two reasons; first, it reflects an increasing demand for formal traceability of measurements and second, it is part of a worldwide move to establish formal national measurement systems widely dispersed in the community. The national standards or metrology laboratory remains, however, the source of the measurement standards and expertise which support the calibration services. Without them, these services could not function. For example, in 1992 the PTB carried out a total of 671 calibrations for the laboratories of the German calibration service DKD. These in turn carried out more than 24000 calibrations for industrial concerns which were then used as the basis of more than 1,3 million internal calibrations in just three of the largest industrial users of accurate measurements *see* Figure 4. Similar figures could, of course, be given for other countries and they illustrate the key role played by national standards laboratories in the support of high technology industrial activity of a country [11]. The national laboratories also, of course, compare their national standards with those of other countries. This is done either through the BIPM or through local regional metrology organizations *see* Figure 5 [12].

7.2. *The need for a research base in measurement science*

Measurement standards are not static. They evolve continually to reflect advances in physics and in response to changing industrial needs so national laboratories must maintain an active research base in measurement science. This is necessary so that national industries can obtain the most advanced and accurate calibrations in their own country. Research in measurement science is a long-term activity that must necessarily be done in advance of industrial and other requirements. Today's research in metrology provides the basis for tomorrow's calibration services.

The national benefits of an active research base in a metrology laboratory are not only long term, they are also immediately available through the expertise that results uniquely from an engagement in active research. Major national metrology laboratories have thousands of industrial visitors each year; they run courses and seminars, and are represented on all the important industrial standards bodies. These close contacts with national industries provide important feedback to the national laboratory on present and future industrial measurement requirements.

The long-term research also provides a fund of knowledge and expertise that frequently leads to unexpected applications of the results of basic research to pressing practical problems. A recent example of this is application at the NIST of silicon crystal x-ray diffraction spectrometry to diagnostic x-ray mammography [13]. The image quality in all soft tissue x-rays is critically dependent on the spectrum of the x-rays, which in turn is controlled by the high voltage (20-30 kV) applied to the x-ray source. It is difficult to measure these high voltages with sufficient accuracy under the conditions required for routine x-ray diagnostics. An elegant solution to the problem has been found from the long-term programme of basic metrological research at the NIST related to the measurement of the crystal lattice spacing of silicon using x-ray diffraction with a view to the development of a new standard of mass based on the mass of an atom of silicon. This work has not yet resulted in a new standard of mass but it has, among other things, led to a great deal of knowledge on x-ray spectroscopy of silicon crystals. A silicon crystal x-ray diffraction spectrometer, developed in this work, appears to be an almost ideal way of routinely measuring x-ray spectra from x-ray diagnostic machines.

The advantages to be gained by having all measurement standards in one institute have long been recognized. The close links that now exist between all areas of advanced metrology through their dependence on basic physics reinforce this view. The fact that research on a wide range of measurement standards is carried out in one location has, in addition to the obvious advantages of scale in terms of common services, the great advantage of concentrating intellectual resources where they can be most easily tapped either from within the laboratory or from outside. The application of silicon crystal x-ray spectrometry to x-ray mammography is in fact a direct result of a request to the NIST from the US Conference of Radiation Control Program Directors for help, which was then circulated within the NIST and came to the notice of those responsible for the silicon crystal research.

A national institution devoted to metrology should also become well known throughout the country, should provide easy access for those needing advice and be clear point of reference for all questions related to measurement. A recent study [14] of what industrial companies expect to gain from contacts with Federal laboratories in the US, for example, showed that easy and direct access to specialized technical resources was voted on equal first in importance with the possibility of collaborative projects. Great emphasis was placed on the need for such laboratories to make widely known the range and depth of their activities and to facilitate outside access. The conclusion of this study should be taken careful note of by national metrology laboratories whose technical resources are often unique in their country.

7.3. *International representation*

Global industrial and commercial activity is increasingly regulated at a technical level through international standards (ISO, IEC) and through international agreements such as those made under the International Radio Consultative Committee (CCIR) or the Convention du Mètre. These agreements and standards are drawn up by international committees whose members are experts nominated by their governments. The scientific or technical competance of the individual expert strongly influences the decisions made by such committees. National interests, which may have important commercial or prestige aspects, thus depend on having strong representation on these committees. In metrology, national representatives on international committees are drawn almost exclusively from national metrology laboratories. It is thus in the national interest that the national laboratory, irrespective of its size, provides good representation for international committees.

7.4. *International cooperation between metrology laboratories*

In the past, international cooperation in metrology was carried out almost exclusively through the BIPM and concerned only national standards at the highest level. This is no longer the case. The development of national calibration services, the certification and accreditation of calibration and testing laboratories has led to international links between these services. It has also led to greater activity in the international comparison of standards at levels other than the national primary ones.

The increase in international activity in metrology at levels other than that dealt with by the BIPM, began in the 1970s with the creation by the Commission of the European Communities of its Community Reference Bureau (BCR), recently renamed the Measurement and Testing Programme. The BCR had as part of its programme the support of applied metrology in the EC countries. The major part of its early effort, however, was the establishment of traceability and good measurement practice in the vast range of chemical analyses related to agriculture, food and, to a lesser extent, medicine. The success of the BCR in showing up, and in due course reducing, some of the very wide divergences that existed between analytical laboratories in different countries of the then European Community has already been remarked upon in Section 5. In 1987 stimulated by the activities of the BCR and the growing level of European collaboration in other areas, the national laboratories of the EC countries, together with a number of those from the EFTA (European Free Trade Association) countries, created EUROMET. EUROMET is a European collaboration in measurement standards and in 1993 has eighteen participating national metrology institutes plus the Commission of the EC. The stated aims of EUROMET are :

i) to develop a closer collaboration between members in the work on measurement standards within the present decentralized metrological structure,
ii) to optimize the utilization of resources and services of members and emphasize the deployment of these towards perceived metrological needs,
iii) to improve measurement services and make them accessible to all members,
iv) to ensure that national facilities developed in the context of EUROMET collaboration are accessible to all members.

Similar regional metrology organizations have since been set up in other parts of the world, notably the Asia/Pacific Metrology Programme, which includes members from the Asia-Pacific region including Australia and China, and NORAMET which comprises the national metrology laboratories of Canada, Mexico and the USA. Similar regional metrology organizations are also being formed in South America and Eastern Europe. At present the most active of these regional organizations is EUROMET. All this regional activity is complementary to that of the BIPM which ensures worldwide traceability of measurement standards. The BIPM now takes care to include, as far as possible, at least one representative from each of the regional organizations in its own international comparisons of measurement standards. For metrology in chemistry, the work of the BCR also stimulated the European laboratories responsible for chemical analysis to form EURACHEM which is to the field of analytical chemistry what EUROMET is to the field of physical measurement. Founded in 1989 by a group of directors of laboratories from ten countries in Europe, EURACHEM now has members from seventeen countries and includes delegates from governments, universities and industry. The aim of EURACHEM is to provide a framework in which analysts can collaborate and improve the accuracy of chemical measurements.

8. The cost of maintaining a national measurement system

Measurement and measurement related operations have been estimated to account for between 3 % and 6 % of the GDP of industrialized countries [15, 16].

The cost of maintaining a national measurement system in an industrialized country is between about 40 and 70 parts in 10^6 of the GDP. For the twelve EU countries the total direct spending on national measurement systems in 1992 was about 400 Mecu, equivalent to nearly 70 parts in 10^6 of the GDP of the Community. For the UK and Germany the figures are similar, but a little less than this. For the USA the cost of the metrology and related activities of the NIST alone, 170 million dollars, represents 30 parts in 10^6 of the 1992 GDP and for Japan the figure is between 20 and 40 parts in 10^6 of GDP depending upon whether or not the industrial metrology at the Prefecture level is taken into account. Not included in the figure of 30 parts in 10^6 for the USA, however, are other costs related to the national measurement system that are included in the EU figures. In the USA, for example, the National Conferences of Standards Laboratories (some 1200 members) and of Weights and Measures Laboratories (members from each of the States) are integral parts of the national measurement system and are not funded through NIST. The announced intention of the

US government to double the direct funding of NIST within three years should be noted. There should, nevertheless, be economies of scale in the USA and Japan which have central national metrology institutes, relative to the EU in which each member nation has its own metrology institute. In some rapidly developing countries in the Asia/Pacific region, expenditure on establishing a national measurement system reaches 100 parts in 10^6 of GDP. In terms of the figures given here, the cost of maintaining a national measurement system represents a few tenths of a percent of the 3 % to 6 % estimated to be spent by industrialized nations on measurement and measurement-related operations.

At an international level, the principal cost of maintaining the international measurement system is that of supporting of the BIPM, which, in 1992, was 7 million dollars. This represents about 0,4 parts in 10^6 of the GDP of each of the member nations of the Convention du Mètre and is on average less than 1 % of what each country spends on its own national metrology laboratory.

9. Final remarks - a personal view

In concluding this overview of the field of measurement science and its role in society, I would like to highlight just a few of what I consider to be the most important features:

- Metrology is an essential part of the infrastructure of today's world.
- The economic success of most manufacturing industries is critically dependant on how well products are made and measurement plays a key role in this.
- Human health and safety depend on reliable measurements in diagnosis and treatment.
- The protection of the environment from the short and long-term destructive effects of industrial activity can only be assured on the basis of reliable and, therefore, accurate measurements.
- Physical theory, upon which all of today's high technology and tomorrow's developments are based, is reliable only to the extent that its predictions can be verified quantitatively.
- There exists a world-wide measurement system maintained under an intergovernmental convention which assures the uniformity and accuracy of today's measurement standards and provides the research base in measurement science that will allow tomorrow's standards to be developed.

- Between 3 % and 6 % of GPD in industrialized countries is devoted to measurement and measurement-related activities. The cost of providing a national measurement system is a few tenths of a percent of this, equivalent to between 30 and 70 parts in 10^6 of GPD. A further 0,4 parts in 10^6 of GDP goes to providing the support for the international measurement system through the BIPM.

At the beginning of this article I referred to the difficulties that sometimes arise in justifying to goverments the costs of national measurement systems - principally for the maintenance of national metrology laboratories. In describing the activities of national metrology laboratories I laid great stress on the benefits that an active metrology laboratory brings to national affairs through its support of industry and the provision of advice to government and national representation on international bodies.

I end by urging goverments to maintain their metrology laboratories and most particularly to maintain their active research base. Without long term research it is not possible to meet industrial requirements for accurate measurement standards and the research base, once lost, can only be re-established at great cost and over a considerable time. The national metrology laboratories are national assets whose influence is largely hidden and diffuse, but represent a significant and cost-effective contribution to national affairs.

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Figure captions

Figure 1. Trends in limiting values of tolerances in normal, precision and ultraprecision regimes [2].

Figure 2. Aerospace geared power transmissions: state of the art and benefits of improved precision. (courtesy Rolls-Royce Limited)

Figure 3. Miniaturization of integrated circuits. (source: Siemens, 1991)

Figure 4. The industrial influence of the 671 calibrations carried out by the PTB for the German calibration service DKD in 1992 shown by the 1,3 million calibration certificates issued by just three of the major industrial users [10].

Figure 5. Lines of traceability within the international metrology system [11].

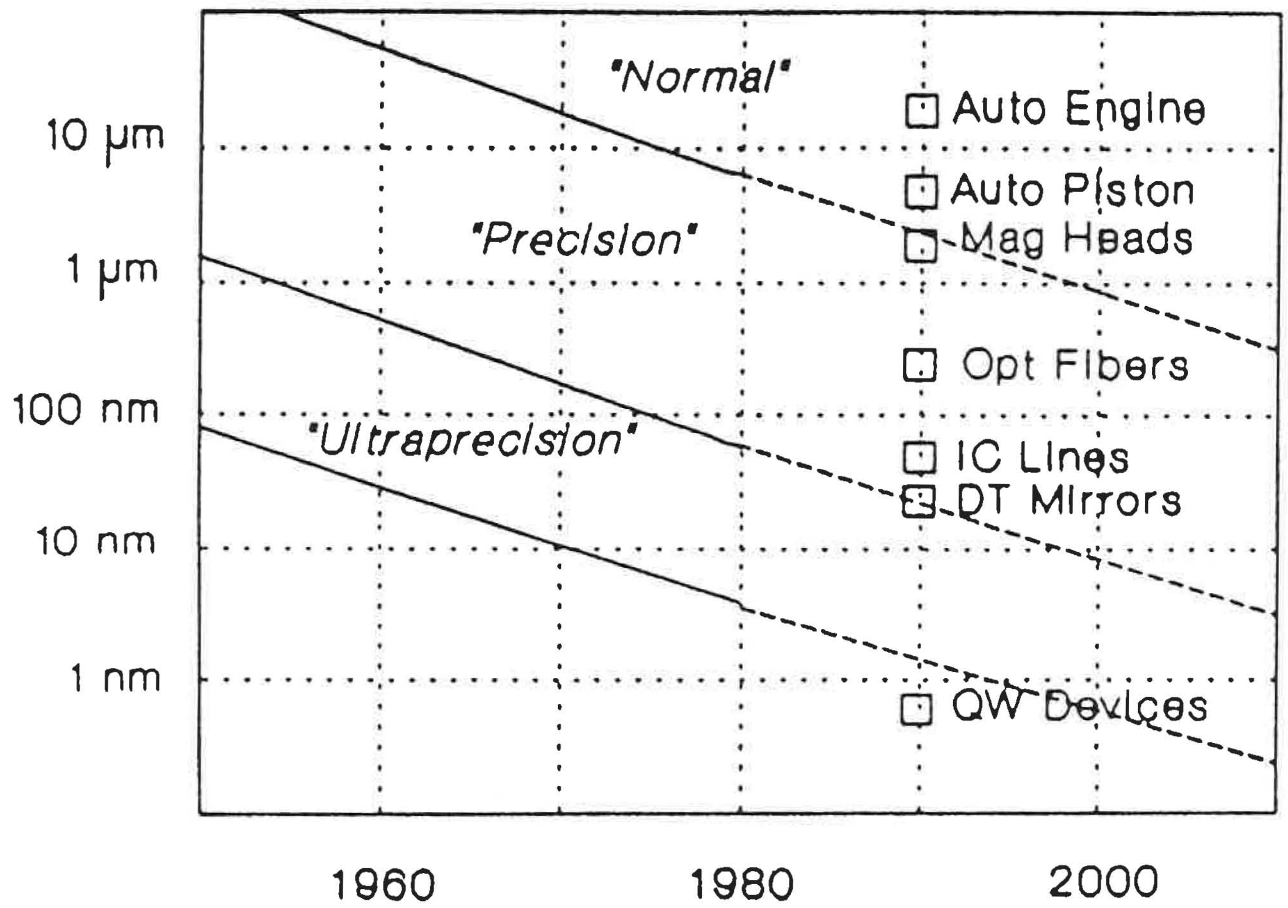

Figure.1 Trends in limiting values of tolerances in normal, precision and ultraprecision regimes. [2]

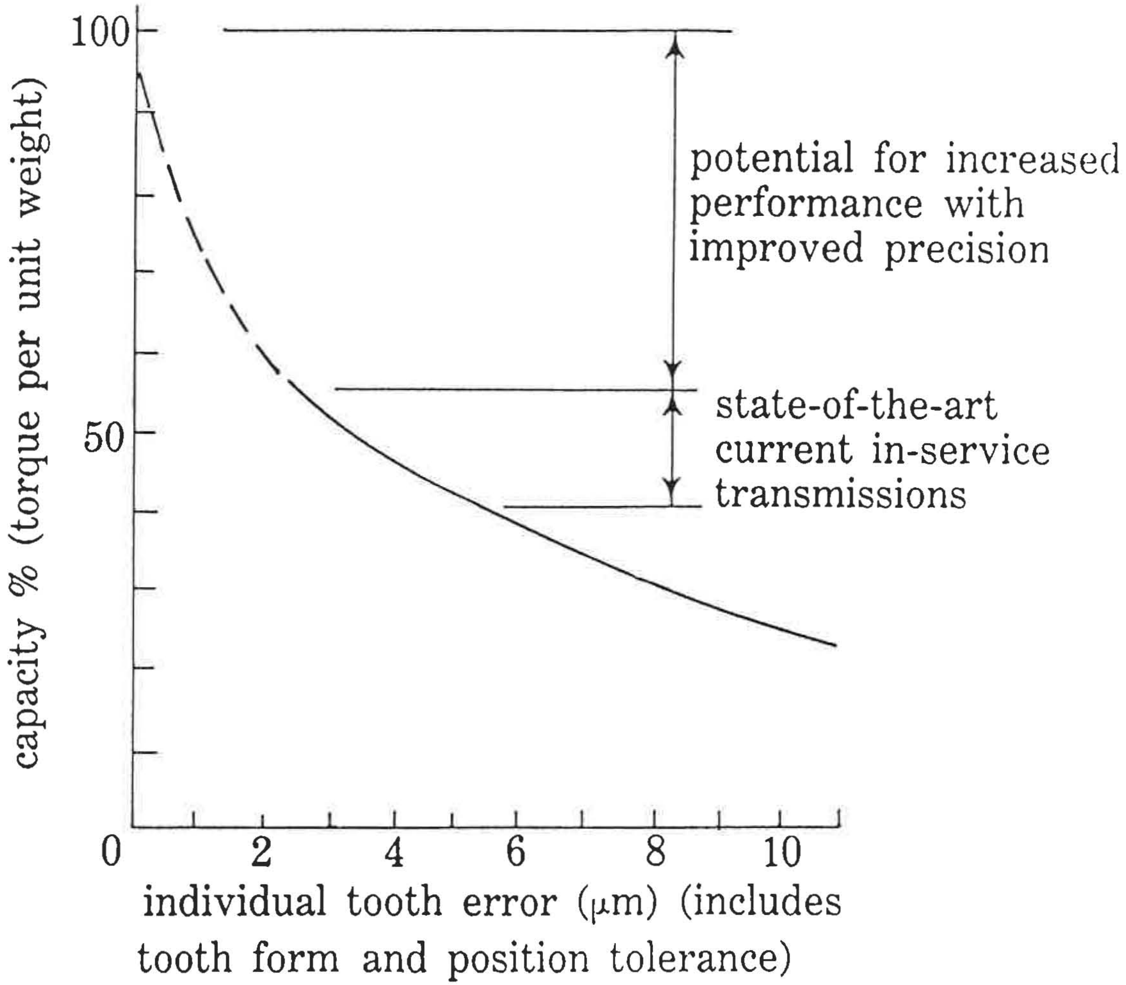

Figure. 2 Aerospace geared power transmissions: state of the art and benefits of improved precision. (courtesy Rolls-Royce Limited)

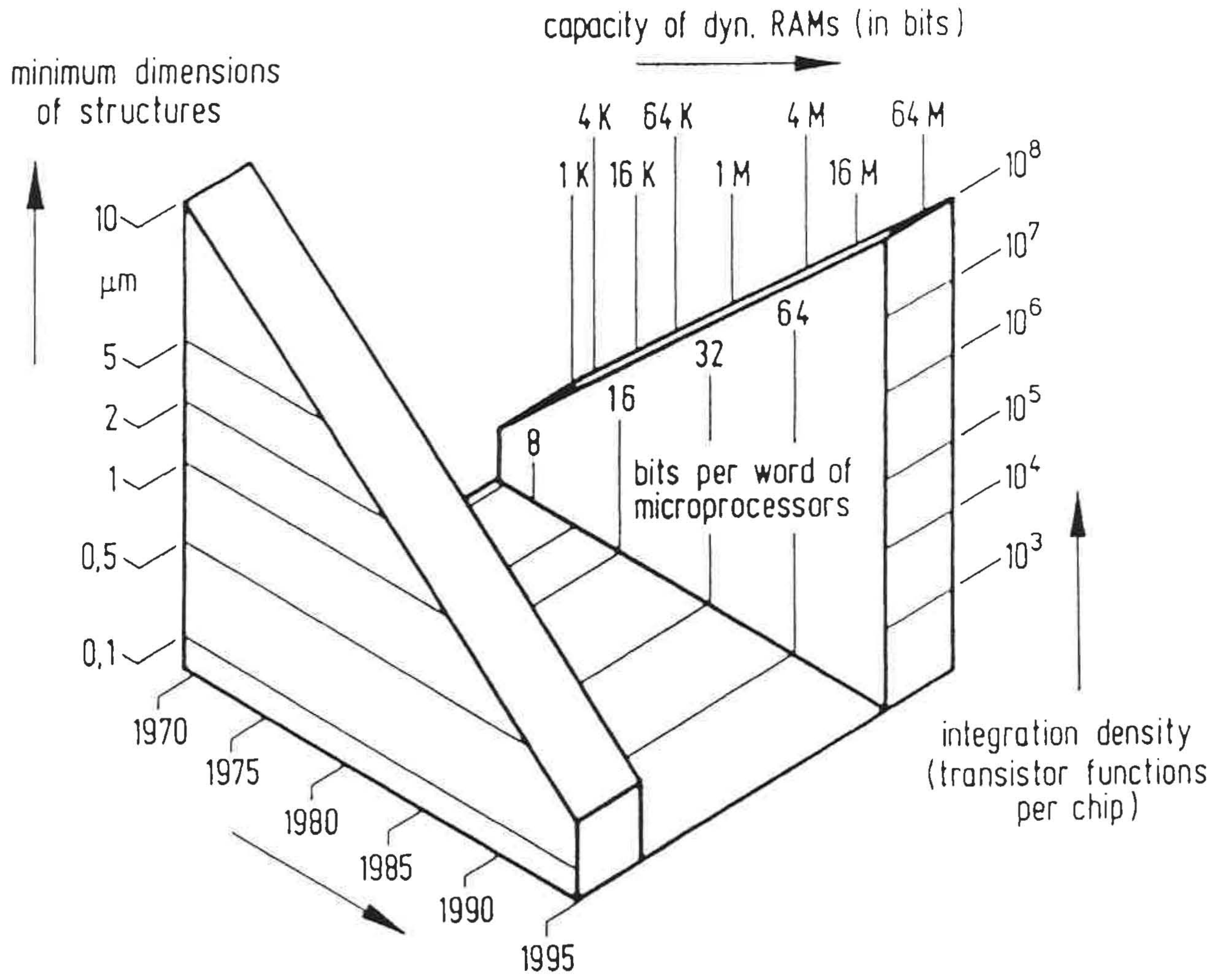

Figure. 3 Miniaturization of integrated circuits.
(source: Siemens, 1991).

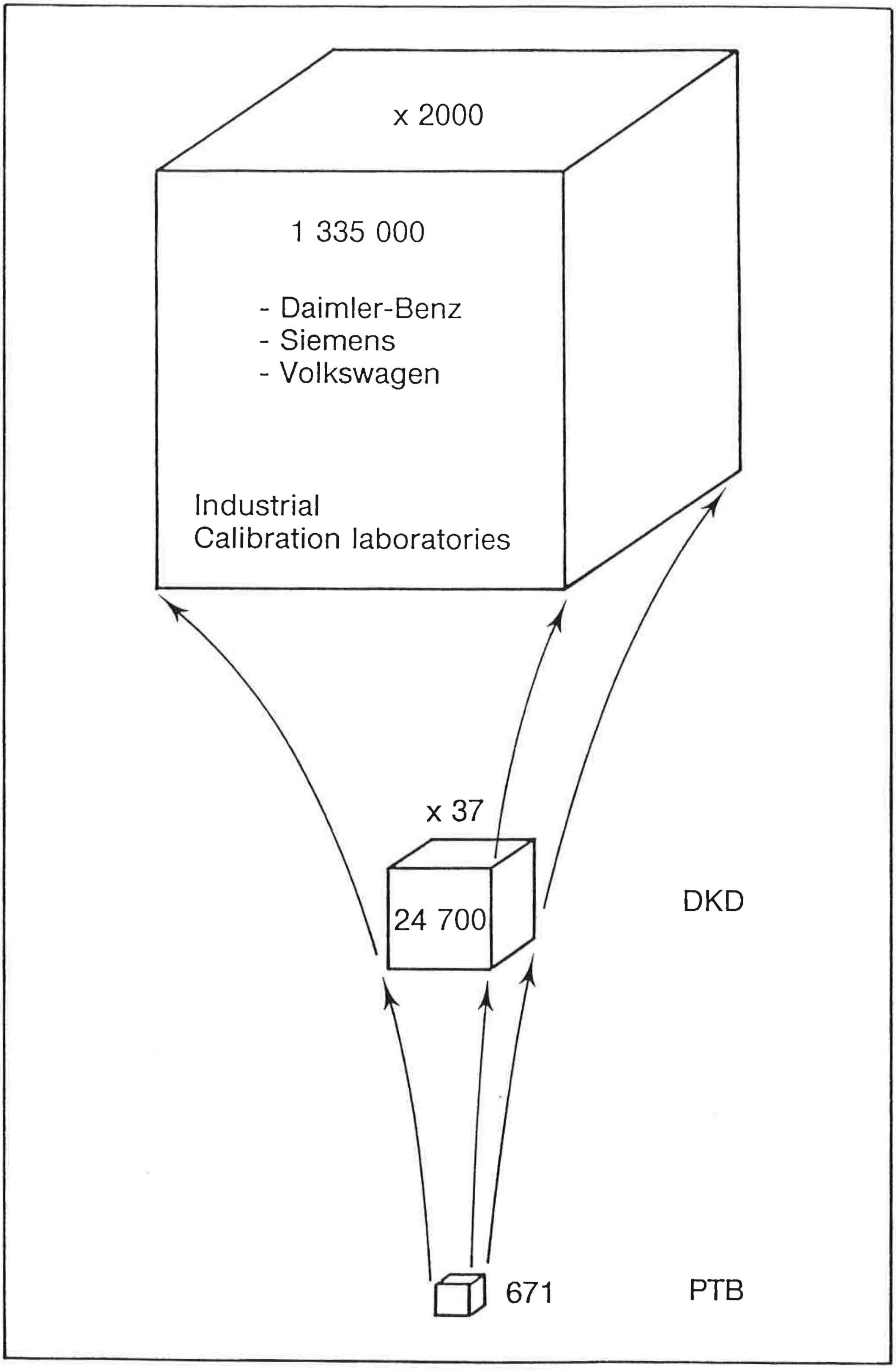
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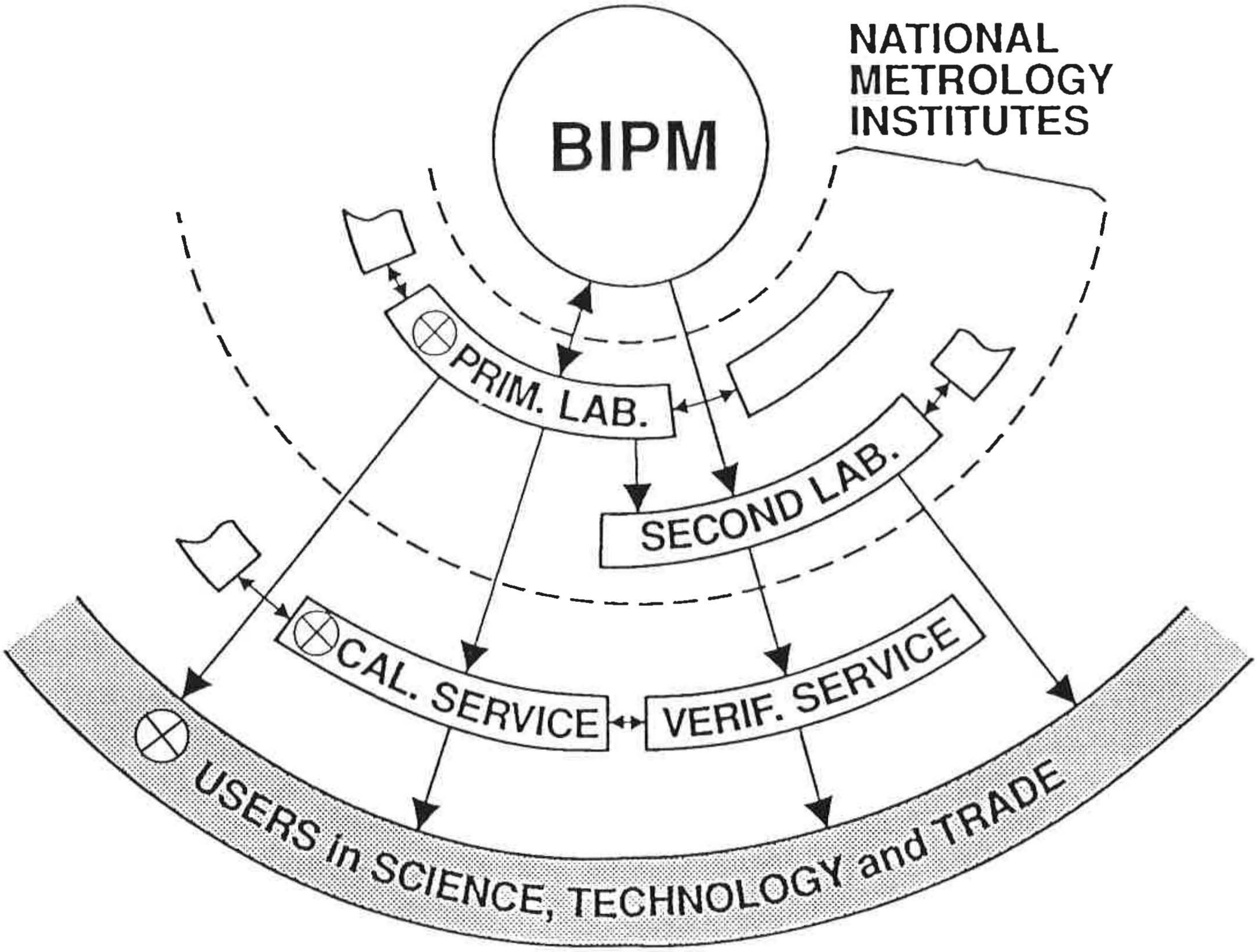
Figure 4



⊗ **Independent quantum-based primary standard**

Figure. 5

Lines of traceability within the international metrology system. (11)

Table 1. Value of Shipments ($B) of Key Sectors of Overall U.S. Discrete-Parts Manufacturing Industry [2].

Discrete-Parts Industry Sector	*Shipments*
Automotive	$ 241 B
Motor Vehicles	$ 205 B
Farm and Construction Equipment	$ 36 B
Fabricated Metal Products	$ 146 B
Aerospace	$ 104 B
Commercial/Military Aircraft	$ 78 B
Spacecraft/Missiles	$ 26 B
Instrumentation, Measurement/Control	$ 108 B
Computer/Communications	$ 96 B
Electronic Components	$ 50 B
Total for Industries Shown	*$ 649 B*

TABLE 2. – *Tolerances on components for a range of modern products* [3]

	Tolerance band	Mechanical	Electronic	Optical
normal machining	200 μm	normal domestic appliances and automotive fittings etc.	general-purpose electrical parts, *e.g.* switches, motors and connectors	camera, telescope and binocular bodies
	50 μm	general-purpose mechanical parts for typewriters, engines etc.	transistors, diodes	camera shutters
			magnetic heads for tape recorders	lens holders for cameras and microscopes
precison machining	5 μm	mechanical watch parts	electrical relays	lenses
		machine tool bearings	resistors, condensers	prisms
		gears	silicon wafers	optical fibre and connectors (multimode)
		ballscrews	TV colour masks	
		rotary compressor parts		
	0.5 μm	ball and roller bearings	magnetic scales, CCD	precision lenses
		precision drawn wire	quartz oscillators	optical scales
		hydraulic servo-valves	magnetic memory bubbles	IC exposure masks (photo, X-ray)
		aerostatic bearings	magnetron, IC line width	laser polygon mirrors
		ink-jet nozzles	thin-film pressure transducers	X-ray mirrors
		aerodynamic gyro bearings	thermal printer heads	elastic deflection mirrors
			thin-film head discs	monomode optical fibre and connectors
ultra-precision machining	0.05 μm	gauge blocks	IC memories	optical flats
		diamond indentor tip radius	electronic video discs	precision Fresnel lenses
		microtome cutter edge radius	LSI	optical diffraction gratings
		ultra-precision *X-Y* tables		optical video discs
	0.005 μm		VLSI	ultra-precision diffraction gratings
			superlattice thin films	

Notes: CCD charge-coupled device, IC integrated circuit, LSI large-scale integration, VSLI very-large-scale integration.

Table 3. Summary of the 1986 recommended values of the fundamental physical constants. [9]

An abbreviated list of the fundamental constants of physics and chemistry based on a least-squares adjustment with 17 degrees of freedom. The digits in parentheses are the one-standard-deviation uncertainty in the last digits of the given value. Since the uncertainties of many of these entries are correlated, the full covariance matrix must be used in evaluating the uncertainties of quantities computed from them.

Quantity	Symbol	Value	Units	Relative uncertainty (ppm)
speed of light in vacuum	c	299 792 458	$\mathrm{m\,s^{-1}}$	(exact)
permeability of vacuum	μ_o	$4\pi\times10^{-7}$	$\mathrm{N\,A^{-2}}$	
		$=12.566\,370\,614\ldots$	$10^{-7}\,\mathrm{N\,A^{-2}}$	(exact)
permittivity of vacuum	ϵ_o	$1/\mu_o c^2$		
		$=8.854\,187\,817\ldots$	$10^{-12}\,\mathrm{F\,m^{-1}}$	(exact)
Newtonian constant of gravitation	G	6.672 59(85)	$10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$	128
Planck constant	h	6.626 0755(40)	$10^{-34}\,\mathrm{J\,s}$	0.60
$h/2\pi$	$\hbar$	1.054 572 66(63)	$10^{-34}\,\mathrm{J\,s}$	0.60
elementary charge	e	1.602 177 33(49)	$10^{-19}\,\mathrm{C}$	0.30
magnetic flux quantum, $h/2e$	Φ_o	2.067 834 61(61)	$10^{-15}\,\mathrm{Wb}$	0.30
electron mass	m_e	9.109 3897(54)	$10^{-31}\,\mathrm{kg}$	0.59
proton mass	m_p	1.672 6231(10)	$10^{-27}\,\mathrm{kg}$	0.59
proton-electron mass ratio	m_p/m_e	1836.152 701(37)		0.020
fine-structure constant, $\frac{1}{2}\mu_o ce^2/h$	α	7.297 353 08(33)	10^{-3}	0.045
inverse fine-structure constant	α^{-1}	137.035 9895(61)		0.045
Rydberg constant, $\frac{1}{2}m_e c\alpha^2/h$	R_∞	10 973 731.534(13)	$\mathrm{m^{-1}}$	0.0012
Avogadro constant	N_A, L	6.022 1367(36)	$10^{23}\,\mathrm{mol^{-1}}$	0.59
Faraday constant, $N_A e$	F	96 485.309(29)	$\mathrm{C\,mol^{-1}}$	0.30
molar gas constant	R	8.314 510(70)	$\mathrm{J\,mol^{-1}K^{-1}}$	8.4
Boltzmann constant, R/N_A	k	1.380 658(12)	$10^{-23}\,\mathrm{J\,K^{-1}}$	8.5
Stefan–Boltzmann constant, $(\pi^2/60)k^4/\hbar^3c^2$	σ	5.670 51(19)	$10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$	34
	Non-SI units used with SI			
electron volt, $(e/\mathrm{C})\,\mathrm{J} = \{e\}\,\mathrm{J}$	eV	1.602 177 33(49)	$10^{-19}\,\mathrm{J}$	0.30
(unified) atomic mass unit, $1\,\mathrm{u} = m_u = \frac{1}{12}m(^{12}\mathrm{C})$	u	1.660 5402(10)	$10^{-27}\,\mathrm{kg}$	0.59