

A brief history of measurement

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Abstract. The aim of this paper is to situate the subject of measurement and metrology in its historical and philosophical context. Everyone agrees that the numeration of objects and the quantification of the characteristics of some simple systems are very ancient practices encountered in any specific civilisation. Indeed the link between measurement and numeration comes from the beginnings. This is recalled here, as are the links between units and money, between references and authority. Then, the paper identifies and exhibits the different epistemological gaps occurred – or occurring – in the history of measurement in the western countries:

- geometry versus arithmetics,
- model versus experiment,
- prediction versus uncertainty,
- determinism versus quantum physics.

Those gaps are described in relationship to the evolution of the internationally agreed system of units.

1 Measurement: Technology or philosophy

1.1 Measurement, experiment and knowledge

Measurement leads to the expression of characteristics of systems in terms of numbers. As explained Lord Kelvin: “When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it in numbers, your knowledge is of a meagre and unsatisfactory kind...”. Indeed the aim of measurement is to give reliable knowledge on objects or concepts. Despite the fact that, in the present paper, the regular historical approach will be considered, one has first to address several transverse questions about experience, numerical value, and knowledge, which will be implicitly referred to hereafter.

What kind of things can be measured? The meaning of experimental measurement is definitely not the same in the different fields, and the frontier of the “measurable” has evolved along time, based on a philosophical background.

How is a numerical value obtained? In practice, such a question is linked to the set up of methodologies, instruments and also reference standards, in order to achieve reliable comparisons and to express results in terms of identified units. It is also linked to the development of the symbolic tools in mathematics and control and computer science; how do those tools apply to experiments?

Why are scientists, and other people, interested in measurement? For the first ones as a tool to increase knowledge, to set up and to test laws and theories in a scientific approach; for the other ones as a part of information, needed for trade and for development, technologies, prediction, control, in order to take a decision without risk or, as emerged slowly in the philosophical approach of measurement, with a stated uncertainty.

1.2 Measurement, scaling and testing

In everyone's life, some measurements and measurement results are received and treated, every time, everywhere... to quantify the characteristics (mass, volume...) used to assess the trade cost of objects; to control the behaviour of owners of technological systems (car speed, air composition above a factory...) which should fit official regulations; to understand and predict natural phenomena (astronomy, weather forecast...); to give confidence in sport performances (race records...); to state as unambiguously as possible medical diagnosis (imaging...), to make and deliver controlled and appropriate medicines; to put objective scales on human senses (hearing, seeing...); to improve the efficiency of technological tools; to characterise aspects of objects (glowness,...) and aesthetics, to strengthen trade; to set up values at the stock exchange; to gather relevant social data of many kinds (age or social income distribution,...); to build indicators in a quality management system and to hear the "voice of customers"; to set up intellectual capacities or to scale emotions (individual scale of pain developed in many hospitals...); etc.

In most cases, to get confidence in measurement data, one has to rely on reference standards, considered as units. According to J.C. Maxwell: "Every expression of a quantity consists of two factors: [...] the numerical value and the unit". Most of what is developed hereafter is related to this ideal case of measurement, dealing with quantities for which, from a mathematical point of view, either the sum or the ratio can be easily defined. In other cases, one has to speak from "scaling", and in most cases when the detailed procedure has to be described and followed to give sense to the result, one has to use the word "testing". However most of the considerations could be applied to domains where the existence of unambiguously defined quantities and appropriate references are not (yet?) well established.

2 Numeration, mathematics and measurement

2.1 Counting units

Among the oldest testimonies of measurement processes in the mid-eastern civilisations, one has to mention the clay balls (6000b,c) found in Mesopotamia: to assess for instance the size of a flock of sheep, the owner was sealing into a large clay sphere as many small balls as there were individuals in the flock, e.g. lambs. The seal was broken, if necessary, to give reliable evidence of the earlier characteristics of the flock. Measurement totally relied on counting. The name of the counting quantum, the "unit" 1, became and stayed the same as the generic name of the reference standards chosen for a given quantity.

Progressively, people were using different shapes for the balls in the same sealed sphere, to include various descriptors of the individuals. They moved then to signs engraved on stones, and later written on RW clay tables. The signs became either pictograms (which appeared also in the far-eastern civilisations) or just lines and symbols. The art of counting, the art of writing seem to be issued from measurement necessities.

2.2 Earliest references

The establishment of reliable references has been made in the early stage, together with the development of a common numeration system for multiples and sub-multiples. Indeed it was linked to political power, as were science and trade, and numerous different systems were established in numerous countries. Museums over the world gather rich collections of old references, and a considerable literature can be found on that subject.

One of the most famous ones is the "Gudea yardstick" for length, established on marble in Lagash at the Sumerian time (2120 bc). The multiples and sub-multiples were taken as simple products by integer factors 2, 3, 5, 6, 10, 60... Egyptian parchments of the Middle-age Empire testify that measurement operations were largely developed in fields as various as land surveying or soul weighing!

2.3 Metrology for exchanges

παντων χρηματων μετρον ανθρωπος

Man is the measure of everything... Of course this statement from the Greek philosopher Protagoras (420 bc) was mainly relying on the philosophical problem of reality and non-reality. However it emphasizes the fact that most practical units became anthropomorphic units. Indeed most needs were also related to anthropomorphic quantities.

Furthermore, quantities [and units] were defined in terms of usefulness, whatever the scientific coherence: different units were used for length (length of objects) and for distance (itinerary measurements). As most coins were relied on noble metals (gold and silver), money was incorporated into the metrological system and mass units and money units usually coincided.

2.4 Geometry overcomes a first scientific epistemological gap

Among the scientific and technical developments of the Greek civilisation were astronomy – the main developed experimental science – and cartography – the main useful tool for navigation, trade and conquests. Arithmetics and geometry became identified fields.

At the time of Euclid, a major difficulty occurring in the previous measurement approach was solved. Let's consider the ratio of two quantities A and B of the same kind. If A and B are commensurable (*i.e.* the ratio is a fraction of defined integers), counting can be used for measurement of A in terms of unit B . But if not, the ratio is properly “immeasurable”. Geometry handles with immeasurable ratios, for instance between the diagonal and the side of a plane square. So geometry has been able to fix the difficulty. However, looking for instance to a length and an area, the units have to be different, and homogeneity should be carefully preserved.

This gave rise to one of the famous measurements of that time: the measurement of the Earth radius, and of the Earth meridian, by Eratosthenes of Kyrene. Using the comparison of the geometric shadow induced by the sun in zenith on a vertical bar translated in different places (Alexandria: $7,5^\circ$; Syena: 0° ... and Meroe more south), situated roughly along the same meridian, he deduced from the distance between the cities (800 km, measured by walking) an estimate of the Earth meridian as $25'2000$ stadions. Despite more than four different stadions were used at that age in different places, it appears that the stadion used was equal to 300 Aegypt roy cubits, or 600 Gudea untis, *i.e.* 158,7 m... This scales Eratosthenes' meridian to 40 000 km. Not bad!

He then has been able to calibrate distances on Earth from the angular measurement of star positions, and to draw one of the first “Parallel-Meridian” geographical map of the known universe.

3 Science and “official units”: Weak links until 1795

3.1 Ideal and pragmatic references up to the XVIII^o century...

In the ideal case, no measurement result should be given without the assessment of the traceability. Every standard, or instrument, should be calibrated against certified references with a defined periodicity, themselves being calibrated along a calibration chain relying on primary agreed reference standards.

The expected qualities of standards are those which give confidence in the use of them:

- * sustainability and stability in time,
- * capacity to be uniformly distributed, in space,
- * accessibility (easy to use),
- * accuracy (a modern quantitative concept for the first two characteristics when the reference does not rely on a material object).

From Roman times to the early XVII^o century, there was roughly no link between “scientific knowledge” – mainly astronomy – and practical units. The latter were relying not on formulas, but on unjustified recipes, algorithms, calculations... They were defined and agreed on a local basis, inside a kingdom, a province, a city, or even a less wide country... They were transmitted – and from time to time coordinated – by local practices: apprenticeship for the know-how, instruments for trade, art and crafts... and science. References were disseminated in such a way and in an extent which were matching most needs. In France, local units were governed by geopolitical authorities. They were anthropomorphic: “*journal*, *hommée*, *fauchée*” were units of area of land, corresponding to the area which could be worked or mowed by one man in one day; the actual area was depending on the shape of the land and the nature of the culture... From one city to the other, the same name could support different practical definitions, and the local “*setier*” was installed at the entrance of each local fair to probe the volumes of cereal exchanged... Coming from east-Mediterranean issues, mass and money were relying on common unit names; it occurred during seasons of famine that prices remained unchanged as quantities were decreasing, for instance for the bread called “*pain de 2 livres*” (weighing quite less !) in the XVII^o century around Paris.

“It was working” as evidence is given by the successful technical realisations of that time, for instance the erection of cathedrals and castles in Europe. Definition of units, diffusion of references, control of truth were delegated to local authorities, and authorities at that time in western Europe and elsewhere were close to religion. Indeed the holy texts (Bible, Koran, Torah...) from the three major monotheisms promote unambiguously the faithfulness in measurement.

3.2 Physical laws in classical sciences: Evidence rather than inter-subjectivity

In fact, to follow the changing role of measurement in science is a way to monitor the human conception of science and knowledge during the Middle-Age and after. The so-called “first scientific revolution” arose during the XVI^o and XVII^o centuries. In mechanics for instance, Galileo was able to set up relationships between parameters of motions. By measurement he observed that proportions were respected between non commensurable quantities: the velocity reached by a falling body is proportional to the time of fall and the height of falling proportional to its square... Kepler used the huge amount of astronomical data collected by Tycho-Brahé to set up some laws of the motion of the planets around the sun, as the proportionality of the square of the period to the third power of the length of the main axis of their elliptical trajectory...

Geometry was giving access to the data, laws were verified and then stated as true. There was no direct major interest in the proportionality coefficients, which we call nowadays fundamental constants. Mechanics was more or less a development of Mathematics. Laws should allow predictable future observations. The deductive approach of Descartes, Galileo, even Laplace should give a justified representation of the world, based on evidence.

During the XVII^o century emerged a different kind of scientific approach, which gave a major role to experimentation. Scientists were attempting to observe new unexplained situations, using instruments taken from craftsmen (pumps, thermometers...). In chemistry, in the field of heat and energy, later in electricity and magnetism, progress relied on the confidence in observers. Bacon, Boyle, Hooke, Newton... established a reliable representation of those phenomena based on inter-subjectivity.

At the end of the XVIII^o century, the diffusion of knowledge, arts and crafts in Europe prepared the convergence between classical and experimental sciences which is described in 4.

3.3 Unification attempts

The increase of trade all over the world (including the voyages to India and China, and the discovery of America) provided an increasing interest towards a coherent measurement system. Many attempts had been already engaged towards unification:

- * at the era of Carloman, probably as heritage of the Holy Roman Empire,
- * in Great Britain, as the unified state emerged (except for the multiples),
- * later in Germany, as the German identity was growing up,
- * in France before the XVIII^e century; in the early age of the country the king conceded to his vassals the right to establish and disseminate their own references for measurements and their own money; he managed to buy back the privilege of the money (Charles V, Philippe II) but failed to unify the measurement system (Philippe VI, François I, Louis XII...); the only domain where units have been largely unified, according to the needs for trade, is the field of shipping in Europe (due to the efforts of the French prime minister Colbert).

But the set up of standards and the calibration of instruments were remaining efficient ways to control the access to a local market and to regulate the trade through taxes. Thus they stayed under the local authorities until the end of the XVIII^e century.

3.4 “To every time, to every nation”

As the French revolution completely modified the organisation of the public authorities, people had to deal with the measurement system. Furthermore the active philosophers (Turgot, Condorcet) or politicians (Talleyrand) were asking for uniformity in references for measurement. This was also asked for by the complaints (“*cahiers de doléances*”) coming from the whole country. Of course most of the involved people would have accepted unified practical references coming from Paris. Nevertheless, the members of the committee in charge of the definition of these new references were scientists (Lavoisier): their answer was an attempt to *universality*, much more ambitious than the search for *uniformity*. The whole system of measurement, established by the French law (*Loi du 18 Germinal an III*, which aims to address to every time and every nation), was relying on a single definition for the unit of length, the metre. All other relevant quantities had units deduced from the metre (the kilogram was, for instance, the weight of a cubic decimetre of pure water at an assessed temperature). The unit of time remained unaffected by this conjunction of classical (for the metre) and experimental (for the kilogram) sciences.

The law also stated that every division of numerical values, including the case of time scales, should be decimal. One can already see today in the *National Techniques Museum* in Paris historical “decimal” clocks...

3.5 The metre is defined as part of the Earth meridian

In the French metric system of 1795, the definition of the metre plays a key role. Two possibilities were discussed.

- The first one was related to the length of a pendulum with a period of one second. Originally studied by Galileo and Mersenne, then by Mouton, Huygens, Richer (in Suriname), Burattini (who promoted a so called “metro cattolico”), such a definition was demonstrated as non-uniform: the period of a given pendulum depends on gravity, and on the place where it is. A choice of the place (Paris, rather than London...) would have restricted the universality.
- The second one was related to the length of the Earth meridian. After the Eratosthenes’ result of 25’2000 stadions, the meridian had been measured in China [Yixing (VIII^ec), Thomas (1702)] in li’s, in Europe [Snellius (1617), Picard (1670), Cassini (1701, 1739)], in Peru [La Condamine (1735–44) – 56 750 “*toises*”], in Lapponia [Maupertuis (1737–39) – 57 422 t]... The Earth was known as flat on the poles, but exhibited a roughly perfect symmetry of revolution around them.

According mainly to political considerations, French people chose the north quarter of the meridian, as “everybody can find one under his feet”. It was stated as 10 000 000 m. French

academicians J.B. Delambre and F. Méchain were in charge of the calibration of the old “toise du Pérou” on the meridian. They achieved between 1792 and 1799 a complete triangulation of the meridian between the north of France (Dunkerque) and the Spanish coast on the Mediterranean Sea (Barcelona, even the Balearics islands). A triangulation is the direct measurement of all angles of a complete figure of numerous triangles using as summits specific prominent points, coming from an origin (Dunkerque) to a destination (Barcelona). The size of the triangles depends on the situation, but does not exceed 20 km. The trick is that, to calibrate angles, one does not need any length reference. By simple measurement of the angles and by further projection on a plane, the whole scheme is determined as soon as one knows the length of one of the segments, whatever it is. As one knows the length of the Earth meridian, and of its fraction between the latitudes (these are angles) of the origin and of the destination. It is then possible to calibrate the length of a given object (which will be a calibrated etalon) on any side of any triangle, some of them being considered as basis. Delambre and Méchain were using the newly constructed repetitive circle by Lenoir and Borda.

The official report of this famous experiment can be read at the Observatory of Paris (available on the website): most of the original data have been preserved by Delambre in the 2000 pages of the report. Information is given on the repeatability, the reproducibility vs. Cassini’s results, the corrections achieved to the angle observations (according to astronomical phenomena, air, specific positions...), the computations performed (by hand). Redundancy in the calibration of the *toise* has been obtained by performing operations on two different bases at the thirds of the travel. The job was not so easy, as it was mainly a time of war in Europe. Méchain was suspecting, until the end of his life, an error in the measurements in Barcelona. Delambre, in his report, remained highly respectful of his older and dead colleague, but wrote severe sentences about the methodology. He gave evidence that there was no hidden mistake, but that some error causes had to be taken into account, giving rise to an uncertainty in the so-called “reduction” of the data.

The relation of this experiment appears as a key point in the evolution of the relationships between science and measurement. According to Méchain, who was essentially a scientist from the XVIII^e, classical sciences had to predict values, and observers should verify them. Any discordance was probably related to an error. For Delambre, who was younger, one could accommodate uncertainty, even in physical laws, as in the case of experimental sciences.

4 The coherence of units and the uncertainty in measurement (XIX^e)

4.1 Uncertainty and statistics

As recalled above, measurement means comparison to a reference, and the traceability of the reference is needed to give confidence in the result (numerical value + unit). However, as errors can occur, as repeatability has to be taken into account, as references can evolve, one has to estimate the reliability of the result in order to be able to take a decision based on it. This is the role of the concept of “uncertainty”.

During the period 1800–1850, there was a large increase in the gathering of data and information. This activity was triggered by the needs: in order to control and administrate states (and empires) in a centralised way, including the colonies overseas; to improve and rationalise production of craftsmen and in industry; to use efficiently steam power and electricity; to develop communications; to address the progress in agriculture machinery; to help education and improve health... Examples are relied to experimental sciences, as tables of atomic weights, refractive indexes, specific heats, animal characteristics... Most of them were outside physics, dealing with land-areas, population, production and market, human characteristics and human skills.

To treat these data, to be confident in them, even if they had been obtained by incomplete counting – we would say sampling –, inter-subjectivity and evidence had to be considered on the same level.

4.2 The second scientific revolution and the third epistemological gap

Classical and experimental sciences linked together during the XIX^e century. Both tried to integrate some of the advantages of the other into their way of representation of knowledge.

In classical sciences [Laplace, Poisson] a lot of efforts was devoted to integrate through a theoretical approach most of the experimental fields, like electricity, heat transfer, etc. The emergence of the atomism and of the principle of elementary interactions was quite successful. On the other hand, there has been an increasing interest in the assessment of the physical laws by experimental results, and in their theoretical interpretation in terms of fundamental constants, which had to be exhibited often for the first time.

In experimental sciences [Fourier, Thomson, Maxwell], most of the phenomena were related with the others by introducing semi-empirical laws between macroscopic quantities. Indeed, the mathematisation of the relationships promoted reproducibility and confidence. At the other end emerged the need to evaluate constants in empirical equations, and thus to fix practical units.

At the same time, mathematics became independent. To summarise the classical sciences tended to unification through a theoretical approach and the experimental sciences through the measurement. One of the key developments of this time is the Gauss experiment on Earth's magnetism. It arose from a practical need: for navigation, a good knowledge of the cartography of the Earth magnetic field, in direction and in amplitude, was needed. Von Humboldt convinced C. Gauss (1831) to take the challenge and to overcome the difficulties, identified mainly as natural ones [the Earth field changes upon place and upon time, and neither model nor calibration are available] and as technical ones [the Gambay's type best compass had a changing magnetisation].

To obtain measurement results independent of the compass and reliable in time and space, Gauss performed absolute measurements by setting up a direct explicit link between the results and the “mechanical” quantities L , M , T , the latter having units fixed by the metric system. He promoted a new scaling law, with no unknown constant, for the relevant derived units, and built a pseudo-coherent system of units for electromagnetism which was later completed by Weber. Furthermore he evaluated the performance of the results through a combination of observations and of best estimates. He developed a rigorous theory of errors, and analysed the dispersion observed. His statistical approach of the measurement was so convincing that he obtained for the experimental results the same kind of level of accuracy and so the same dignity, as was reached in astronomy.

4.3 Carl GAUSS' heritage

Beyond his role in the experiment described above, and beyond the reminder of his name in the famous Laplace-Gauss distribution curve, C. Gauss appears as a key scientist in this third epistemological gap for measurement. He introduced the statistical approach in measurement. Indeed Gauss (1777–1855) had been educated in the classical sciences in astronomy and mechanics, and in mathematics through Fourier and the experimental sciences. Among his colleagues, students or heirs, one finds scientists engaged in the set up of coherent units for absolute measurements, as Von Helmholtz (1821–1894) who promoted a theory of measurement. One finds also people engaged in the estimation of the “quality” of measurement, even in a sense wider than uncertainty on physical quantities, as Quételet (1796–1874), who applied methods from physics to social data and concepts. Gauss finally inspired scientist like Fechner (1801–1887) who developed, at the frontier between physics and social sciences, psycho-physical methods for the measurement of perception. Helmholtz, Quételet and Fechner are considered in their own fields as pioneers.

4.4 The emergence of the Convention du Mètre

The industrial revolution and the unification of experimental and classical sciences gave rise to important progress in sciences and techniques: instruments became transducers from, or

to, electrical quantities. The dissemination of sensors and actuators of common kind linked industrials and craftsmen with science. An intense activity was developed around technologies, and around the set up of references and standardised methods. Universal fairs were organised to exhibit technological progress and to promote countries. Specific laboratories and networks of existing ones were set up [Observatories (1834), BAAS (1821), Commission for electrical units (1861)]. They were preceding the foundation of National Metrology Institutes (NMI) in most countries at the end of the XIXth century (NPL, PTR, NBS, LNE...).

An intense diplomatic activity conducted by France (delayed by the Prussian-French war) issued in 1875 in a general convention to establish common references for the physical measurements, the Convention du Mètre. This international treaty is governing up to now the international metrology. At the beginning, it gathered 18 countries (among them USA but not GB which joined in 1884); in 2008 more than 50 countries are members of the Convention and several others are associated members. One of the responsibilities of the bodies instituted by the convention is the development of the International System of Units (SI), which is *de facto* in use in almost every country all over the world.

A General Conference (*Conférence générale des poids et mesures* CGPM) meets every four years, and examines the recommendations of an international scientific steering committee (*Comité international des poids et mesures* CIPM) which meets annually to handle general affairs and to take proposals. CIPM is assisted by several consultative committees, specific to a domain of activity; there is also a transverse Consultative Committee for Units (CCU) which cares for the SI. A pilot-laboratory (*Bureau international des poids et mesures* BIPM, www.bipm.org) of 70 people is established near Paris, and acts as a referee for the international traceability of the references, promoting interlaboratory comparisons. It is also deeply involved in international cooperation and R&D projects.

Among the first resolutions of the CIPM/CGPM one finds the adoption of new definitions for the metre and for the kilogram. Both in 1889 were finally related to prototypes made of an alloy of Platinum (90%) and Iridium (10%). The mass prototype K was a right cylinder with equal height and diameter. Copies can be calibrated against it with a 10^{-8} relative uncertainty. K remains in 2008 the support of the definition of the unit of mass. The length prototype was a long bar with a specific X profile and a plane surface on which lines have been engraved. 1 m was the distance between two of those lines when the bar was at a given temperature. This definition was changed in 1960.

By implementing such definitions, the deciders at the end of the XIXth century were turning back, more or less, to science. They were addressing the main needs of the period, entirely devoted to the development of the production, giving easy to use and accurate references in the range of the human sizes.

On the other hand scientists were making rapid progress in the understanding of the components of matter, and J.C. Maxwell was recommending: "If we wish to obtain standards of length, time and mass which shall be absolutely permanent, we must seek them (...) in the wavelength, the period of vibration and the absolute mass of these imperishable and unalterable and perfectly similar molecules...". No such definitions will arise until 1960.

5 Towards a coherent measurement system based on science

5.1 Today's SI: An increasing scientific basis

The international system of units (SI) is presently based on the definition of units for seven quantities, considered as dimensionally independent, which permit to cover all the fields of electrodynamics, statistical thermodynamics, physico-chemistry and induced fields, and photometry. The choice of the units corresponds to an evolutionary and pragmatic approach of the definitions all over the XXth century.

The unit *second* has been related to the Earth motion, and to astronomical phenomena, until 1967. It is now related to the period of an identified electromagnetic transition in the radiofrequency range in a given atomic system, e.g. the caesium atom. Such a definition, seen

as sustainable and uniform, fits the recommendations by Maxwell. The *metre* is since 1983 related to the propagation of light in vacuo. The definition fixes the numerical value, in SI units, of the velocity of light c in vacuum. In practice references are spectral atomic lines. Their frequencies have been calibrated against the caesium clock. The theory of electrodynamics is thus completely immersed in the definition of the metre, even with its relativistic characteristics. This theory is not yet denied by experiment. The unit of mass *kilogram* remains unchanged since 1889. Studies are engaged to fix a limit to the evolution of K, by comparison with some fundamental constants. The *ampere*, unit of intensity of electrical current, is expressed since 1948 using the Laplace law describing the force exerted between two conducting wires of well defined geometry holding currents. One can easily show that this definition is the same as another fixing an exact SI value for the magnetic permeability in vacuum μ_0 . As c has also a fixed value, the “impedance of vacuum” $Z_0 = \mu_0 c_0$ is also fixed, as is the electrical permittivity ϵ_0 . The *kelvin*, unit of thermodynamic temperature [which is the only measurable quantity in thermometry] relies since 1968 on a fixed value for the temperature of the triple point of pure water, when liquid, solid and gaseous phases remain at equilibrium. The *mole*, unit of quantity of matter, is obtained since 1971 by counting the individual atoms in 0,012 kg of ^{12}C . Finally the *candela*, re-defined in 1979, links photometric measurements, expressed when optical quantities are observed using a “mean human eye” characterised by an international CIE standard, to the radiometric measurements expressed in energy units. The *candela* is an example of the set up of action spectra for photo biological measurements inside the SI, in that case for the human vision.

The evolution in the SI over years can be illustrated by the evolution in the definitions of the metre. At the time of the French revolution, the metre was related to a macroscopic absolute reference, the Earth meridian. Afterwards, it became the length of a prototype, which gave more facilities to get accurate copies of the reference [indeed the position of the axis of the Earth poles, relative to the Earth, had been demonstrated as non-fixed, which introduced variability in the definition of 1795]. The metre remained unchanged until 1960, despite the fact that tremendous progress had been achieved in the understanding of the nature of matter, of the properties of atoms, and more generally in the verification of quantum mechanics. Spectroscopists defined at that time another length unit, called ångström and linked to a line in Hg, to increase the accuracy of the comparison of spectral wavelenghtes in light-atom interaction. However, the world was more interested in building roads, bridges, factories, than atomic systems for scientists. As the poor accuracy of the interferometric techniques did not allow the transfer of the properties of stability of atomic wavelengths to the macroscopic domain of the metre, there was no advantage to change the definition. Finally in 1960, experimental progress in optics lead the CIPM to take the decision, and the metre became a defined multiple of the wavelength of a stated atomic transition in a particular atom, e.g. ^{86}Kr , chosen for the robustness of the experimental “mise en pratique” of the etalon. In the seventies, measurements of c in metres per second relied on atomic references (Maxwell type) for the metre and for the second. Experimentalists demonstrated that the main source of uncertainty in such experiments was coming from the reference for the metre itself. As physicists believed in the electromagnetic theory, with c as a fundamental physical constant, the evolution towards the 1983 definition based on c was obvious. In every case, a gain was obtained in accuracy by changing the definition; of course the new definitions were implementing a reference inside the confidence interval associated with the previous one, so that no bias should appear.

Perspectives can be foreseen in the same direction. Except for the second, for which scientists are probing atomic clocks in the optical domain to benefit from much higher quality factors in the resonance lines, all other units could see their definition changed in a quite predictable future. Experiments tend to replace the present definition of the kelvin by one fixing the SI value of the Boltzmann constant, introducing statistical thermodynamical laws in the SI definitions. The so-called watt-balance experiments, associated with the quantum electrical conservation etalons, give access to the expression of a mass in terms of the Planck constant h . The Avogadro constant N_A can be estimated by counting, either in an ion beam or inside a quasi-perfect macroscopic crystal. After the fixing of SI values for these constants, the SI would

not be so different from the ideal “theoretician” system of units where those constants (let’s say four of them) are taken as units and assigned to 1.

Of course, so much modern physics in the SI would increase the accuracy at the top of the calibration chains, and so improve traceability. Some previous references will have to be reclassified, especially for mass measurements. New technologies of measurement will arise, as it has been the case with the new definition of the metre after 1983 (laser trackers, etc.).

5.2 Towards coherence on a shared planet

Measurement and testing have nowadays the status of objective referees in a huge number of cases, in a lot of different fields, addressing many quite different situations, for instance security and health care for nuclear control, sustainable development, law contests, various regulations, performance evaluation, etc. Numerous intergovernmental or independent institutions have been established in specific fields (CIIRad...). Strong efforts are handled by the BIPM to promote technical support for recognition of the scientific work achieved in terms of references and to establish links with those other fields.

Furthermore, for general purposes, a *Mutual Recognition Arrangement* (MRA) for the calibration certificates issued in the different countries has been signed in 1999. There is no longer any obstacle to trade due to calibration, and the hidden infrastructure to ensure world-wide traceability is now formalised: a public database gathering the results of interlaboratory comparisons (the Key Comparison Data Base KCDB) is maintained by the BIPM, and indicates the degree of equivalence of the national references in the different fields, estimated from experimental secured results. One can think about the fact that more than a century separates the signature of a technical and scientific treatise, and the set up of an international arrangement having direct impact on trade controls.

These characteristics have been made possible and have been accepted because of the simultaneous development of certification and of accreditation for calibrations, tests, analysis, all over the world. Performance obtained is no longer guaranteed by the individuals themselves. They are evaluated, as is the management system, by a third party body, organised in such a way that the accreditation, which it can deliver, is internationally recognised. This remains true even in the case where official public agreement is expected. On the other hand, an increasing role is played by standardisation (ISO, IEC...). Standardisation bodies elaborate, validate and write down consensual methods for measurement and testing, define methodologies for the evaluation of uncertainty (EN 13005) and for the statistical approach of the measurement (ISO 5725) as well as they set up referential for the implementation and the certification of quality management systems (ISO 9000, ISO 17025). Fortunately, international bodies acting on closely linked fields recognise usually equivalence between the different quality management standards.

The limits of the worldwide common approach in the field of measurement rely on strategic priorities of countries, for trade, for defence, or technological independence and leadership... In the field of communications, common standards appeared only as practical solutions to overcome arbitrary regulations, and were very soon widely and wildly disseminated. Another example can be found in the positioning systems on the Earth. Using the new definition of the metre, one can deduce from the observation of an organised set of satellites, orbiting around the Earth, its own position with a typical 10 metres uncertainty using a cheap receiver... The American GPS system is presently operating, with 28 stations. The Russian GLONASS system relies on 10 others satellites, and the European project Galileo will take signals from 30 new ones. Attempts are also in progress in China (Beidou). All these systems have shared the bandwidth for the signals, and we can hope, but are not sure, that one individual will be able in the future to benefit from the whole set, as the time scale should be coordinated in so called GNSS signals.

6 As a conclusion: Towards a fourth epistemological change

The European Union (EU) has set up in Lisbon new perspectives towards the “society of knowledge”. The improvements in technologies, and the scientific developments in the

understanding and the manipulation of fundamental objects, give today access to a “new technology wave” related to micro- and nano-sciences and technologies. At such a scale, the classical description of the characteristics of systems fails. One has to consider a new quantum approach, which is scientifically established but not at all disseminated among users and citizens. We are reaching the frontier of common knowledge, where scientists have to define the relevant quantity for the problem they have to solve. Classical laws no longer operate, and for instance as someone asks for the size of an atom, the answer should depend at least on the probing technique.

Studies at the nanoscales lead metrology at the frontier of measurement. There is a lack of references in many fields. For instance in mechanics, roughness etalons have mainly been developed on a regular perturbation basis. For Scanning Tunnelling Microscopy (STM), for Atomic Force Microscopy (AFM), very few references are available, and most are badly linked to the metre. In any case, no real effort has been made up to know to disseminate these concepts to a wide public, despite the fact that measurement plays a tremendous social regulation role.

Measurement has been a decisive part of the human activity since the beginnings of any social organisation: it is directly linked to objective information and to validation of knowledge. It took part in the set up of most of the three main epistemological gaps in the history of science. A complete new field of knowledge linked to micro and nano-objects, sensors or actuators, mainly understood from a physical point of view, is in front of the humanity in most of the applied fields (technology, biochemistry, etc.). Of course progress in the definition of relevant quantities, in the set up of measurement procedures, etc. is needed. But an evolution in the way of thinking to quantities and to handle with measurement results at this scale seems also unavoidable.

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References

The author is a physicist. He has rather no specific skills to write articles related to the history or the philosophy of science. The text above expresses personal views, based on experience and on readings which are surely incomplete. He thought that the choice of references which he could have made cannot match the requirements of the citation index procedure. So he decided to restrict the bibliography to the information that can be inferred from the text itself.