A TEMPORARY HISTORY OF METROLOGY

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Annotatsiya: Ushbu maqolada Stefan Xokingning taniqli formulasi va yondashuvi bo’yicha yuritiladi. Metrologiyaning o'tmishi, hoziri va kelajakgi haqida so’z boradi. O'tmishi boy holatlar bilan ajralib turadi, ularda faqat katta burilishlarga olib kelganini ko’rishimiz mumkin. Hozirgi paytda kvant fizikasi dunyosining metrologiya olamidagi evolyutsiyalar haqida gap ketadi. bu xalqaro birliklar tizimidagi (Si) tegishli o'zgarishlar bilan. Metrologiya texnologiyasining haqiqiy holatini belgilaydi. Kelajak keng qamrovli metrologiyaga, spektakl va domeni bilan ajralib turadigan holatlari bilan ajralib turadi. Shu munosabat bilan metrologiya tadqiqot va rivojlanish uchun yuqori istiqbolli sohani tashkil etadi.

Kalit so’zlar: Metrologiya tarixi, birliklar tizimi, metrologiya institutlari, aniqlik, noaniqlik, amaliy metrologiya

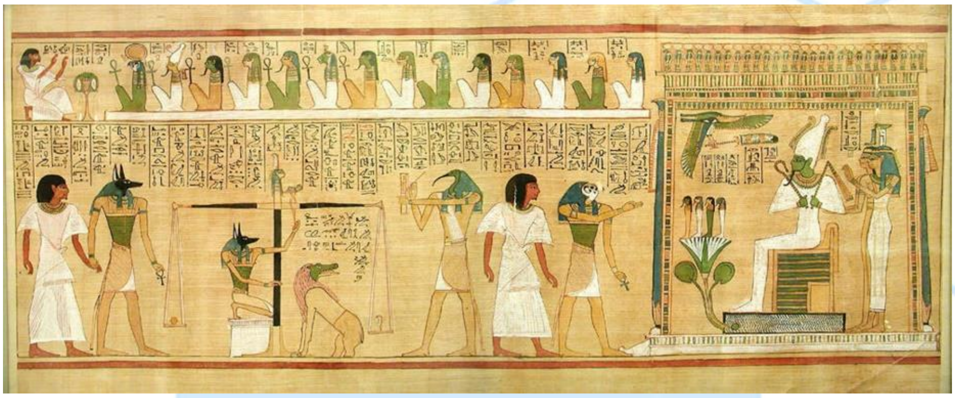
Annotation: In this paper, we take the freedom to paraphrase Stephen Hawking's well-known formula and approach, for a reflection about metrology. In fact, metrology has a past, a present, and a future. The past is marked by a rich series of events, of which we shall highlight only those which resulted in major turns. The impact of the French Revolution is indisputably one of them. The present corresponds to a significant evolution, which is the entry of metrology into the world of quantum physics, with the relevant changes in the International System of units (SI). An apercu of the actual state of the art of metrological technology is given. The future is characterised by a persisting need for a still enhanced metrology, in terms of performance and domain covered. In this respect, soft metrology seems to constitute a promising field for research and development.

Keywords: Metrology history, unit system, metrology institutions, accuracy, uncertainty, performance, soft metrology

Аннотация: В этой статье мы позволяем себе перефразировать известную формулу и подход Стивена Хокинга для размышлений о метрологии. На самом деле у метрологии есть прошлое, настоящее и будущее. Прошлое отмечено богатой серией событий, из которых мы выделим лишь те, которые привели к крупным поворотам. Влияние Французской революции, несомненно, является одним из них. Настоящее время соответствует значительной эволюции, которая представляет собой вхождение метрологии в мир квантовой физики с соответствующими изменениями в Международной системе единиц (СИ). Дан краткий обзор современного состояния метрологической техники. Будущее характеризуется сохраняющейся потребностью в еще более усовершенствованной метрологии с точки зрения производительности и охватываемой области. В этом отношении мягкая метрология представляется перспективной областью исследований и разработок.

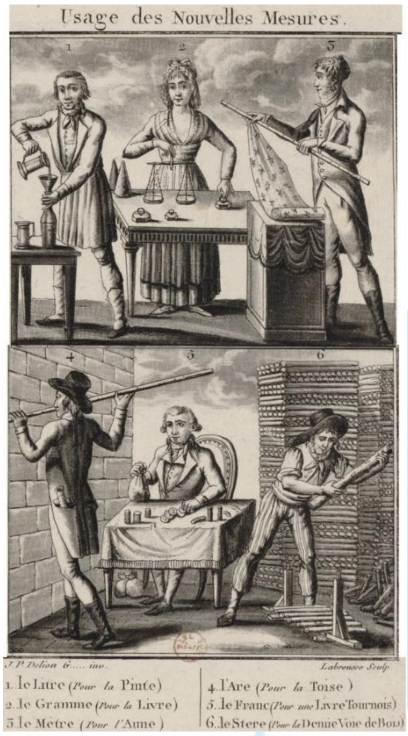
Ключевые слова: История метрологии, система единиц, метрологические учреждения, точность, неопределенность, производительность, мягкая метрология.

The most ancient past. The four great antique civilisations, China, India, Egypt, and Mesopotamia, have all had early a knowledge of metrology. In China, archaeological discoveries demonstrate the use of a decimal metric system as soon as 1600 B.C. Around 200 B.C., at the same time the whole country was unified, a unique unit system was also spread into it. The accurate dimensioning of Egyptian pyramids witnesses of an advanced mastery. Significant research works on the subject have been led by University Paris 7. The well-known papyrus of Hunefer (1300 B.C.) brings a poetic illustration thereof (Fig. 1).



The middle ages and monarchic times. Although very different, these two long history periods present common features concerning metrology. The political power was very disseminated in the middle ages, and was on the contrary very centralised under monarchy, which sometimes confined to absolutism. The feudal system, characterised by dispersion, subsisted in some way under monarchy. The problem regarding metrology was the same in both cases: the affirmation of authority. Every king, lord, town council, monastery, etc. had a tendency to define its own units, as a sign of its power, according to the principle "a king, a law, a weight, a measure". Hence, a great number of different units, also different according to the nature of the goods, measured. Thus, a pound of weight was different for wheat, barley, or flour. Just to illustrate the problem (but, in fact, innumerable examples of this could be given), the measurement of surfaces in the Généralité de Paris (the surroundings of Paris), in 1780–although a late date − made use of the unit arpent, for which existed at least 48 definitions. Moreover, each of these definitions used specific subunits, the length perche being worth here 20 feet, there 25 feet, and yet elsewhere 22 feet 6 inches. Very complicated transactions resulted of this, voluminous manuals and many calculations were required for the unavoidable conversions.

The progress brought by illuminism and the French Revolution. The intervention of the French Revolution in the field of measurement and metrology had social and ethical purposes. The unit system should be unique and equal for all, a goal consistent with the motto of the Republic, and with the expectations of the population as collected by the cahiers de doléances (peoples' claim books). The use of the decimal system introduced drastic simplifications, especially for the determination of surfaces and volumes. These simplifications applied to any citizen, enabling him to proceed to easier exchanges with others, and hence increasing in general welfare. In fact, the Revolution imposed both things, still unfamiliar, which were decimal numeration and a simplified measurement unit system. In most domains the proposed reforms were successful, and progressively adopted by other countries, first in Europe, and later beyond (Fig. 2).



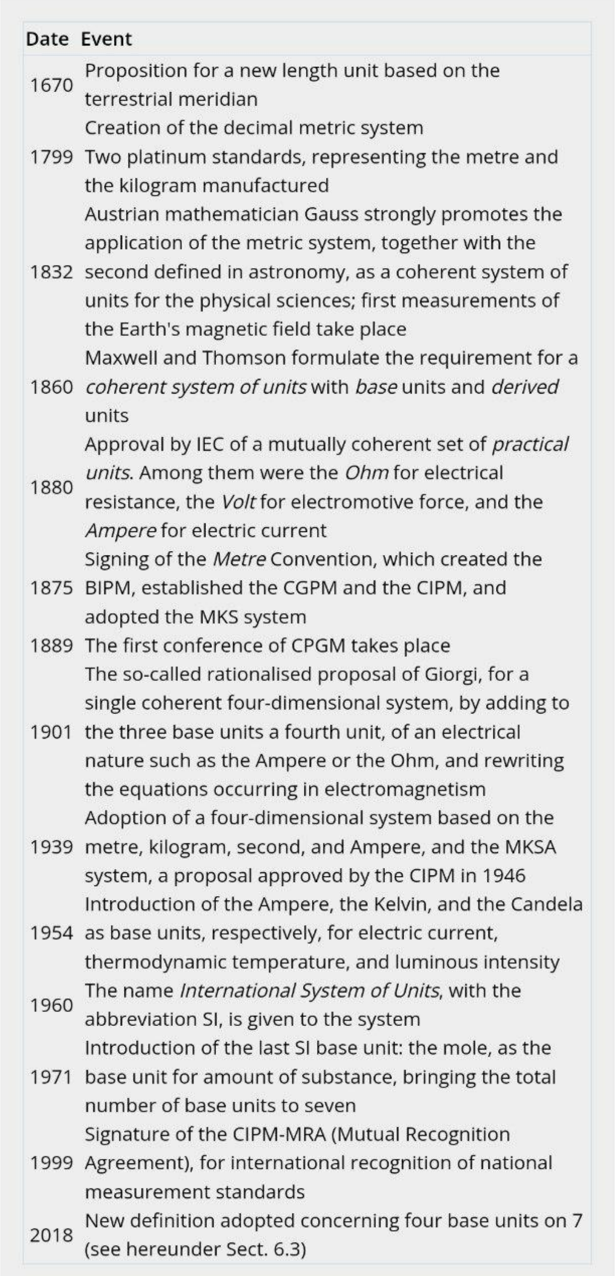
However, it should be noted that the attempts of revolutionists in the domain of time were unsuccessful. The goal was to implement, in addition to the revolutionary calendar, weeks of 10 days, hours of 100 min, and minutes of 100 s. But the way to count and display hours and days is something so familiar to everyone, that this reform has always remained unpopular and was finally never applied. Also, the proposition to use the quarter of the tenth million part of the terrestrial meridian was not due to the Revolution, but was much older, first made by French mathematician Gabriel Mouton a century before (1670). This occurred just two years before French theatre author Moliere described, in the Learned Ladies, the current state of the minds about women willing access to science: not very advanced at that time.

From 17th to 21th century

The main evolutions in the field of metrology during this last period have been the development of scientific discoveries, the intensification of exchanges, and the settlement of international institutions.

Table 1. proposes an overview of these events, in a summary of 14 steps.

Table 1. The most important milestones of recent metrology history.



Date	Event
1670	Proposition for a new length unit based on the terrestrial meridian
1799	Creation of the decimal metric system Two platinum standards, representing the metre and the kilogram manufactured
1832	Austrian mathematician Gauss strongly promotes the application of the metric system, together with the second defined in astronomy, as a coherent system of units for the physical sciences; first measurements of the Earth's magnetic field take place
1860	Maxwell and Thomson formulate the requirement for a *coherent system of units* with *base* units and *derived* units
1880	Approval by IEC of a mutually coherent set of *practical units*. Among them were the *Ohm* for electrical resistance, the *Volt* for electromotive force, and the *Ampere* for electric current
1875	Signing of the *Metre* Convention, which created the BIPM, established the CGPM and the CIPM, and adopted the MKS system
1889	The first conference of CPGM takes place
1901	The so-called rationalised proposal of Giorgi, for a single coherent four-dimensional system, by adding to the three base units a fourth unit, of an electrical nature such as the Ampere or the Ohm, and rewriting the equations occurring in electromagnetism
1939	Adoption of a four-dimensional system based on the metre, kilogram, second, and Ampere, and the MKSA system, a proposal approved by the CIPM in 1946
1954	Introduction of the Ampere, the Kelvin, and the Candela as base units, respectively, for electric current, thermodynamic temperature, and luminous intensity
1960	The name *International System of Units*, with the abbreviation SI, is given to the system
1971	Introduction of the last SI base unit: the mole, as the base unit for amount of substance, bringing the total number of base units to seven
1999	Signature of the CIPM-MRA (Mutual Recognition Agreement), for international recognition of national measurement standards
2018	New definition adopted concerning four base units on 7 (see hereunder Sect. 6.3)

Today's situation

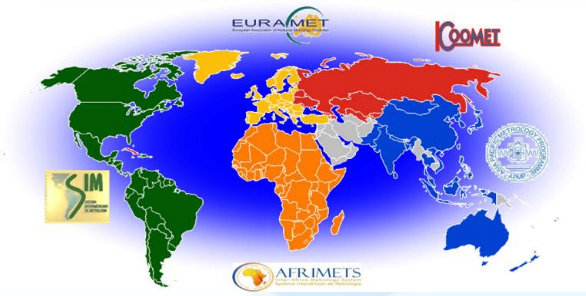
The international institutions. The context today for metrology is fortunately more cooperative than competitive. A set of international institutions, closely linked to one another, have taken place:

-Conférence Générale des Poids et Mesures (CGPM);

-Comité International des Poids et Mesures (CIPM);

-Bureau International des Poids et Mesures (BIPM).

These institutions have received authority to act in matters of world metrology from the Convention of the Metre (a diplomatic treaty between 51 nations initially, but today approved by almost all nations). This particularly concerns the demand for



measurement standards of ever increasing accuracy, range, and diversity, and the need to demonstrate equivalence between national measurement standards. The Convention was signed in Paris in 1875 by representatives of 17 nations. The National Metrology Institutes (NMIs), such as PTB in Germany, or LNE in France, constitute the local relays of the international institutions. The global organisation is completed by World Regional Institutes (RMOs), according to the map in Figure 3.

The regional institutes are less known than NMIs; however, their role is important. They have responsibilities:

− to facilitate traceability to primary realisations of the SI;
− to coordinate comparisons of national measurement standards;
− to make mutual reviews of technical competencies and quality systems;
− to cooperate in metrology research and development;
− to operate joint training and consultation; and
− to share technical capabilities and facilities.

Examples of RMOs are:

− EURAMET (Association Européenne des Instituts Nationaux de Métrologie);
− AFRIMET (Intra-Africa Metrology System − supported by the Technical Cooperation of PTB);
− COOMET (Euro-Asian Cooperation of National Metrological Institutions);
− APMP (Asia Pacific Metrology Programme).

For a more efficient organisation, world regions are sometimes splitted into subregions. For instance, MAGMET (Réseau Maghrébin de Métrologie) is a subregion of AFRIMET. The significant role of CAFMET (African Committee of Metrology) is also to be mentioned, as a key factor in the creation of AFRIMET. Among other tasks, the international institutions have issued a set of fundamental documents: the VIM (International Metrology Vocabulary), the GUM (Guide to the expression of Uncertainty in Measurement), and defined the rules for mutual recognition between NMIS, for national measurement standards, and for calibration and measurement certificates (CIPM Mutual Recognition Arrangement − 1999).

The unit system. The 11th CGPM (1960) adopted the name Système International d'Unités (International System of Units, abbreviation SI), for the recommended practical system of measurement units. SI units are divided into two classes: base units (7) and derived units. To have a realistic approach of practices, these two unit sets are completed by the so-called SI-compatible units, SI-temporarily compatible units, and SI-non-compatible units [7]. Base units are recalled in the diagram.

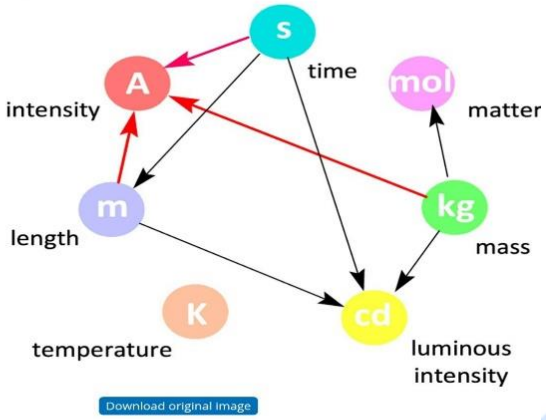
Base units are the following:

− second s (time);

– metre m (length);
– kilogram kg (mass);
– ampere A (current);
– Kelvin K (temperature);
– Candela c (luminosity);
– mole m (matter).

It can be seen that in this arrangement, many units were dependent from other units as shown in Figure 4.

Fig. 4



The most recent changes. The 26th CGPM has taken place in November 2018, and has approved several significant changes through its Resolution A [8]. Goals of this evolution have been recalled, i.e. to build a system that would be “uniform and accessible world-wide for international trade, high-technology manufacturing, human health and safety, protection of the environment, global climate studies and basic science, stable in the long term, internally self-consistent, and practically realizable”. Thus, values of seven general constants, as described hereunder, whose numerical value was initially obtained by experimentation, have been defined as exact values. The impact of new definitions. New definitions of units will have an impact on reproducibility data, according to (Tab. 2): In fact, this impact is weak and will be visible mainly for NMIs.

Table 2 Impact of new definitions of the SI base units.

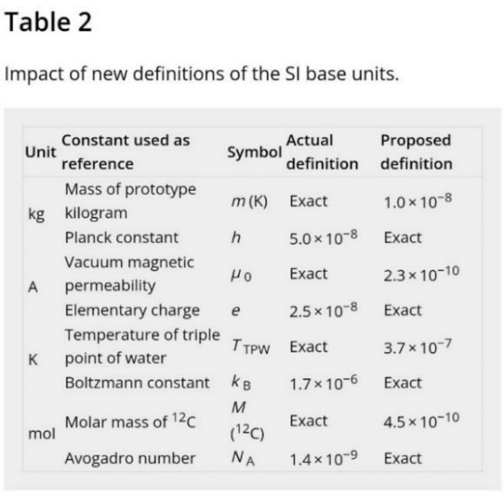


Table 2

Impact of new definitions of the SI base units.

Unit	Constant used as reference	Symbol	Actual definition	Proposed definition
kg	Mass of prototype kilogram	m (K)	Exact	1.0×10^{-8}
	Planck constant	h	5.0×10^{-8}	Exact
A	Vacuum magnetic permeability	μ_0	Exact	2.3×10^{-10}
	Elementary charge	e	2.5×10^{-8}	Exact
K	Temperature of triple point of water	T_{TPW}	Exact	3.7×10^{-7}
	Boltzmann constant	k_B	1.7×10^{-6}	Exact
mol	Molar mass of ^{12}C	$M(^{12}C)$	Exact	4.5×10^{-10}
	Avogadro number	N_A	1.4×10^{-9}	Exact

The next steps. What means metrological performance? This performance relies on the following factors:
- the range accessible to measurement; and

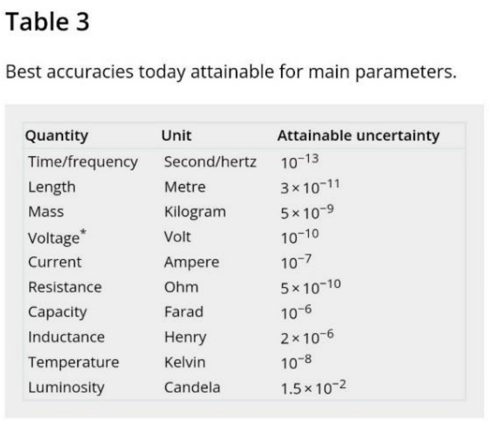


Table 3

Best accuracies today attainable for main parameters.

Quantity	Unit	Attainable uncertainty
Time/frequency	Second/hertz	10^{-13}
Length	Metre	3×10^{-11}
Mass	Kilogram	5×10^{-9}
Voltage*	Volt	10^{-10}
Current	Ampere	10^{-7}
Resistance	Ohm	5×10^{-10}
Capacity	Farad	10^{-6}
Inductance	Henry	2×10^{-6}
Temperature	Kelvin	10^{-8}
Luminosity	Candela	1.5×10^{-2}

- the accuracy of such measurement, i.e. the associated uncertainties. Performance aimed at fundamental research. It can be observed that the most accurate quantities are “mechanical” ones, i.e. time, length, and mass. Among these, time is the most precise. Performance of electrical quantities comes after, and is quite good; thermal quantities are somehow under, and lastly luminous quantities have rather limited accuracy, due to the fact that physiological aspects necessarily enter into the measurement process. Nonetheless, the need for accuracy is not the same for fundamental research, for industry, and for trade. Table 3Best accuracies today attainable for main parameters.

Performance aimed at industry. Considering industry in general, it may be observed that provisions are progressively taken to anticipate and implement the new SI definitions [13,14]. Concerning, more precisely, electrical industries, it can be regularly observed, during accreditation assessments of test laboratories, that the designers of a product have used as little as possible of costly materials, such as copper. Hence, product characteristics sometimes very close to the limits permitted by international standards. Conformity decisions, taken in such situations, may be difficult. Accurate measuring equipment can help in some way to raise the difficulty, but in any case if the measurement uncertainty is not taken into account, the decision remains doubtful. Hence, a true need for a performing metrology, to associate with uncertainties treatment. Anyway, strictly speaking, a measurement value without uncertainty remains meaningless. The Fluke 5730A calibrator represents a good example of a modern equipment, providing extended capabilities and a good safety margin for calibration laboratories (Fig. 6). Such modern equipments allow to handle the risk of wrong conformity decisions, thanks to a Bayesian approach, using the notion of “guard bands”.

5730A calibrator. Source: Fluke.

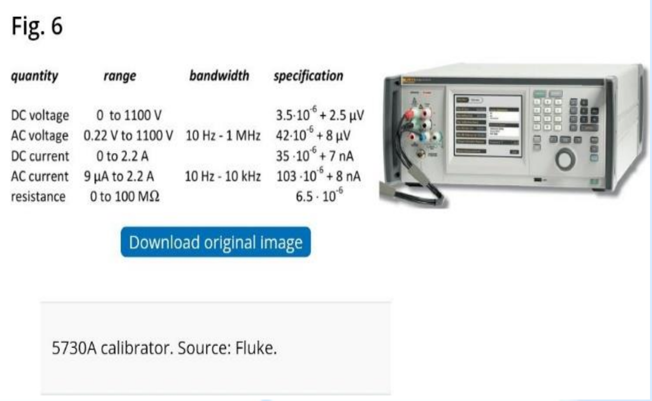


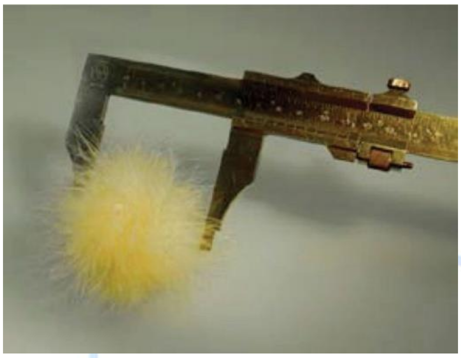
Fig. 6

quantity	range	bandwidth	specification
DC voltage	0 to 1100 V		$3.5\cdot10^{-6}+2.5\ \mu V$
AC voltage	0.22 V to 1100 V	10 Hz - 1 MHz	$42\cdot10^{-6}+8\ \mu V$
DC current	0 to 2.2 A		$35\cdot10^{-6}+7\ nA$
AC current	9 µA to 2.2 A	10 Hz - 10 kHz	$103\cdot10^{-6}+8\ nA$
resistance	0 to 100 MΩ		$6.5\cdot10^{-6}$

5730A calibrator. Source: Fluke.

8.2. A farther future

The domains covered by fundamental and applied physics extend every day. So must do metrology [15]. Beyond its traditional goal to help specification and understanding of objective reality, metrology today also investigates the domain of human perception (i.e. the so-called “soft metrology”) (Fig. 7).



This is to be applied for instance to:
psychometric measurement or perceived feeling (colour, taste, odour, and touch);
qualitative measurements (perceived quality, customer satisfaction, etc.);
econometrics and sociometry (opinion); and
measurements related to human sciences: biometry, behaviour, intelligence, etc. Soft metrology sections are already active at NIST (USA) and NPL (UK). Also the European Commission has funded some research within the N.E.S.T. programme "Measuring the Impossible" [16]. There is likely a wide future for such works.

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