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DISCUSSION FORUM

Failures of the global measurement system. Part 2: institutions, instruments and strategy

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Abstract Between 1998 and 2007, the governing body of the Treaty of the Metre conducted three strategic reviews of future global measurement needs. This critical review examines those reports with a view to determine whether or not this institution is capable of resolving the impasse, discussed in Part 1, that has existed for many decades in the manner of communicating the results of chemical measurements. Examining both the main substantial recommendation and the explicitly stated common presuppositions of the three reports leads to the regretful conclusion that the institution can neither resolve the impasse nor meet significant future global measurement needs. Therefore, the onus is on chemistry itself to consider carefully the units with which the results of chemical measurements may be communicated clearly and concisely to their users without the semantic confusions inherent in the International System (SI) of measurement units discussed in Part 1. At the larger level, the institutional failure of the Treaty to fully grasp the dynamism of 21st century science, technology and industry raises concerns for world trade and global economic coordination.

Keywords Treaty of the metre · Chemical measurement · Strategy · Instrumentation · Mole

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Introduction: global metrology and its strategic vision

Wise administrators have said that the committee is a marvellous invention which very effectively and efficiently enables very clever people collectively to make very silly decisions. In global metrology, we have an embarrassment of administrative riches. Most of this proliferation of committees is not formally part of the Treaty of the Metre, although the Treaty's administration is not without experience in the creation of committees. The complexity of global metrology committee infrastructure evolved historically largely as a result of the Treaty's inability to provide measurement leadership in practical measurement and the emerging sciences and technologies that lay outside its purview of pure scientific measurements in classical mechanics and electrodynamics. For example, information is a quantity of some fundamental significance in the 21st century, unrepresented in the SI.

Administration of the Treaty at the highest level is the General Conference (CGPM) which comprises representatives from the National Measurement Institutions (NMIs) of the signatories (there is also a designated observer status) which meets every 4 years. Between conferences, a handpicked expert International Committee (CIPM) performs administrative functions, implements the decisions of the Conference and prepares the agenda for the next Conference. It was intended this body not contain the representatives (de facto or otherwise) of nations or institutions. It is assisted by a number of consultative committees for the various quantities that are the basis for the International System of measurement units (SI).

In 1999, the Conference received the report it had requested 4 years earlier from the Committee to report on long-term needs, and then requested the Committee to report to the next Conference on long-term needs, which

Conference in its turn also requested the Committee to report to the next Conference on long-term needs. This atypical hyperactivity in long-term strategy has a number of interesting features. Firstly, all three reports by CIPM to CGPM [1–3] were inside jobs. No need was felt to go outside the pool of ideas, culture and experience of the administration and generally a great deal of satisfaction was expressed in the current general state of affairs in global metrology. Member States were assured that the pyramidal national measurement system with the NMI at the apex of a metrological and calibration hierarchy was indeed the best of all possible worlds. More than that: it was the only possible world. None the less all were agreed that difficult challenges lie ahead, that technologies are rapidly changing and thus increased funding is required for NMIs and the operations of the Treaty itself. The successive reports take pains to say they are consistent with the one that went before and were necessitated by the truly unprecedented and rapid technological changes that were unforeseen in the previous reports, so a sort of addendum was needed. This is a tribute to their strategic foresight.

Concerning metrology in chemistry, all devote a few paragraphs to it and all agree that it is important and a very recent thing, as if some time in the 1990s analytical chemistry had suddenly appeared from nowhere. In each of these reports on the future of the Treaty of the Metre, there is little awareness of history. It is simply historically false that the principles of good measurement, or metrology or analysis (call it what you will) sprang into existence as claimed in the wake of the Treaty of the Metre. Practical measurement and weights and measures predate recorded human history, but consider also this remarkably modern understanding of the goal of accuracy:

"My goal in analysis is not to obtain results which are absolutely exact—which I consider as only to be obtained by accident—but to approach as near accuracy as chemical analysis can go."

That was one of the founders of modern chemical analysis, Berzelius (1779–1848). Now, consider this equally remarkable expression of the ethic of measurement (that measurements ought to be what they purport to be):

"A chemist who would not take an oath guaranteeing the authenticity, as well as the accuracy of their work, should never publish their results, for if they were to do so then the result would be detrimental, not only to themselves, but to the whole of science."

That was the other founding father of modern analysis, Fresenius (1818–1897).

Closer examination of the three strategic reviews reveals some differences between them, some evolutionary trends and a couple of significant omissions. While there are progressive differences in emphasis, urgency, lists of newly fashionable but previously unanticipated technologies and newly confected needs, rising enthusiasm for more consultation and cooperation, the creation of more committees and requirements for more money, there is one startling difference.

A proposal of substance?

Only the first report has a recommendation and proposal of substance for a new kind of action. This is the introduction of a regular series of "key comparisons" between national and regional metrology institutes to establish "degrees of equivalence". It is a surprising admission that this has not been done previously. It should have raised alarms in the capitals of all industrialised countries. Why has this not been happening for at least the past half century? Intercomparisons have been commonplace in chemical analysis for many decades and were further developed by accreditation agencies on a large and systematic scale across a wide range of quantities of economic and social significance. Proficiency testing has been a subject of great interest to this journal (ACQUAL) since its own inception. On the face of it, "key comparisons" are simply a rebadged form of proficiency comparison. It is not really a core competency of the Treaty organisations–accreditation organisations (or suitably accredited specialist proficiency testing organisations) are the independent and unconflicted place where the skills exist (or ought to exist) to conduct thoroughly rigorous intercomparisons, at any level. Intercomparisons are a tool (and only a tool) of transparent confirmation of relative competence, relative compatibility and relative equivalence of measurement results.

There is a more troubling aspect to this activity. The "reference values" used to establish the "degrees of equivalence" are established by the appropriate consultative committee on the basis of the data of the "key comparison" itself. This is a worrying use of the term "reference value" and needs rethinking. It is a regrettable example to the rest of the world because use of the term "reference value" to describe proficiency test results can be metrologically hazardous. It requires great care and is better done not at all.

There is a metrological fable that has been retold many times [4]. It concerns an eccentric retired sea captain who lived in the hills overlooking Zanzibar City and fired a ceremonial cannon and raised the ensign at exactly noon each day. He knew it was noon from his chronometer which he took pains to accurately set whenever he passed the watchmaker's window in town. The watchmaker knew his clocks were accurate because he checked them daily when that punctilious captain on the hill fired his cannon at noon exactly. If you need to think about what is wrong with that, ask would you be a willing passenger in an international airliner landing at an airport which used such a system mutually calibrating control tower and departure lounge (and even if done with impressive precision)?

There is iron logic to this. In metrology, intercomparisons have many useful purposes if done openly and transparently for correct and clearly stated reasons with clear protocols. But if not, they will only tend to propagate systematic error whenever the "Zanzibar syndrome" applies. It applies whenever a so-called "reference value" is derived from nothing but manipulation of the very same results that are being compared. Thus begins potentially a self perpetuating circular system where A calibrates to B who takes their calibration from C who calibrates··· to A. The application of sophisticated statistics to produce a "reference value" can be of no avail. We know this with the same certainty that we know there can be no *perpetuum mobile*. The issue is control of systematic error. We all know of cases where the outlier has proved in the end to be the accurate result. This is a vital issue. Confusing messages from the highest authorities are not helpful. There are plenty of interested people only too willing to believe that participation in an intercomparison creates a traceable reference. It is a bad example to the rest of the world.

That is not the end of the difficulty. There is a presumption in the minds of some that NMIs are by definition accurate and the procedure therefore justified. Firstly, if that is true, why bother with intercomparisons at all? It is also a presumption directly contradicted by historical fact. Fallibility is the condition of science. NMIs are not free from systematic error, despite their exhaustive search for sources of bias and thorough evaluation of uncertainties. The clearest example is the much discussed significant "fluctuation" in the speed of light from about 1928 to 1945 [4–9]. Further discussion is now academic as the administrative decision in 1983 to fix its value by conventional definition has effectively blindfolded science to a significant empirical question [10].

Finding and making freely available reliable, common, appropriate, secure and fast anchors for the measurements our world requires is the proper core function of the Treaty organisations. It is an extremely difficult, demanding and often perplexing task, but endless intercomparisons that would be better and transparently done by other parties more disciplined in the skills required is not a credible strategy. It is a diversion.

The only possible way...

Nor is it a credible strategy to simply claim that the current arrangements via the national measurement institute hierarchy are the *only possible* way to meet the world's measurement needs. There is a particular emphasis on this in all three strategic reports. No argument or evidence is given. There is no humble contemplation that it might be simply the best or just better. No alternatives are even thinkable.

There are three big trends in measurement evident for many decades. They scarcely rate a mention and their implications for the global measurement infrastructure are discussed not at all. The trends are as follows:

The instrumentation revolution

The massive PITCONN conference for analytical instrumentation is testament to this, and anyone who has worked behind a laboratory bench in the last half century has felt it viscerally. It is much more than that. Historians generally distinguish three "big revolutions" in the modern history of science [11] with a fourth well underway as you read. Big revolutions change the way we view the world and embrace changes in concepts, practice, institutions and the relationships of science to the wider society including politics, economies and technology. The first was the well-known seventeenth century revolution, characterised by a realisation of the importance of experiment, the Newtonian synthesis, the beginnings of "amateur" scientific societies and recognition by secular rulers that such knowledge was applicable to the useful arts of all kinds and to be encouraged for that reason. The second is associated with the rise of understanding of the importance specifically of measurement in the early 1800s. The third occurred around the end of the nineteenth century with the understanding of probability and statistics, rising professional institutions, research centres and organised training. It was the apotheosis of classical mechanics. It was said at the time that with the then current understanding of physics, human knowledge was more or less complete, no radically new knowledge was possible and all that was left to do was to dot the i's and cross the t's, measure to more and more decimal places and apply it all to worldly works. There was physics and there was stamp collecting. These were said by eminent physicists of the age shortly before Planck's work on black body radiation and Einstein's miracle year and decades after Mendeleev's presentation to the Russian Chemical Society on the dependences between the properties of the elements and the deaths of Darwin, Mendel, Babbage and Boole. That was the culture and world view of the Treaty of the Metre.

From the start, science and technology demonstrated dynamism beyond the imaginings of the Treaty and its institutions. In the second half of the last century, a practical unifying theme began to emerge. We are in the middle of the fourth big scientific revolution, associated with the rise in the importance of instrumentation in all areas and the institutions and the ideas and the myriad technical and industrial applications associated with it [12–15]. Analytical chemistry has played a leading role in that revolution and modern instrumental chemical measurement is concerned with routine analysis at trace levels, with analytes, matrices, numbers and speed of analysis that in mortal memory were all quite beyond the reach of thought even in the most advanced laboratories. This has been driven by both changing technology and social need ranging from support of high-technology industry to environmental management to forensic need. The end is not yet in sight. The linking to indicators of cheap throwaway biosensors capable of identifying and quantifying virtually any desired analyte has only begun. The economic weight of medical costs, pathology and diagnostics around the world will ensure that this accelerates although the techniques are by no means limited to such analytes and applications. Biosensors illustrate well the interdisciplinary nature of practical measurement technology of the past decade. Neither nature nor nanotechnology respect walls between the biological, the chemical and the physical.

In addition to all of that is the large-scale application of information technologies and expert systems to instrumentation. The most important technical aspects of many modern instruments are their software, information linkages and database. Instruments are becoming “clever” and even “virtual”. A sensor in one part of the world can relay signals to an instrument in another which can relay information to data processing facilities in another and compare the result to a massive database existing nowhere in particular. All this is done on a large scale and automatically. Finkelstein observed back in 1982 [16] that there was a large epistemological gulf between the general theory of measurement and the understandings of those who design and engineer instruments. It is still there, now considerably larger.

These developments pose profound challenges to metrology in both practice and theory that are quite absent from the strategy considerations of the Treaty of the Metre organisations.

Intrinsic standards

The goal to replace artefactual reference standards and to anchor measurements in independent and constant properties of nature is a long running and well-known trend and today only units for mass are realised by artefacts. Intrinsic standards can refer to many things. Blevin [1] for example distinguished realizations of units from reproductions of units. Realisations are a literal material example of the definition of the unit, whereas reproductions utilize inference from well-established scientific knowledge. What all usages have in common is that some known natural, constant, material phenomenon is produced under well-controlled experimental conditions and a well-accepted value (and uncertainty) is assigned to a well-identified property of that phenomenon which is then used as an etalon (or measurement reference standard) for the appropriate quantity to create and calibrate a measurement scale. This practical reference value is effectively arrived at by independent reference to nature and does not require comparison to any further reference standards for that particular quantity. Primary methods of measurement may also effectively produce intrinsic standards, and chemists are quite familiar with the concept if not the terminology. It is what they are doing when using coulometry to characterise a sample in terms of chemists’ moles or weighing a sample of material of known identity and purity to prepare a standard solution expressed using the chemists’ mole (but not if expressed in grams).

Intrinsic standards are widely used and are increasingly being integrated into instruments. A common example is the use of frequency-stabilized lasers to produce internal reference standards for length in instruments used by surveyors and builders. One advantage is that a temporal, changeable artefact based on human decision and worldly power is replaced as anchor by a constant feature of nature [17]. However, even more important is the dramatic reduction in the whole calibration chain and its hierarchy that intrinsic standards enable. These can be literally “do it yourself, on the spot” primary etalons if all the correct conditions are fulfilled. For most practical purposes, all that is required is a valid reproduction of the relevant unit at an uncertainty appropriate to the intended use. The corollary of course is the great unsayable. What then of the utterly essential, irreplaceable role of national measurement facilities? On at least one of their core functions, they are near redundant. If nature is to be the anchor, the keepers of the standards need to reconsider what is their mission. These are considerations distressingly absent from these strategic reviews.

The two trends, the instrumental revolution and intrinsic standards are rapidly converging. They raise two fundamental and interwoven issues: metrological control systems for instruments and transparently ensuring that the production of intrinsic standards is appropriate and performed correctly and competently. The first is firmly in the field of practical measurement and is something with which weights and measures administrators have a great deal of experience and expertise. It will be recalled that the International Organisation for Legal Metrology (OIML) came into existence because the Treaty organisations were unable or unwilling to take responsibility for practical measurements. There are OIML recommendations concerning instrumentation, and an example of their effective and efficient operation in a national metrology system for instruments was described in [18]. The second issue that of assuring competence is of course a proper function of accreditation agencies and a matter in which they also have considerable expertise. Much more needs to be learned but these are the institutions that should be taking a leading role in meeting future global measurement needs.

There is no doubt that these issues need much more serious consideration. We cannot even start to consider them on the presuppositions of the strategic reviews prepared by the administration of the Treaty of the Metre. The pyramidal calibration hierarchy with NMIs at the apex and practical measurement spread along the base is, according to these strategic reviews, the *only possible* way to meet the world's future measurement needs. It is at odds with the plain facts.

The evolution of national measurement laboratories into strategic instruments of national interest

It would be false also to suggest that NMIs have not evolved. They have, and very considerably since their inception. The real evolution however has not in its fundamentals and missions been towards global metrology but rather towards competitive national interests. For developing nations, a national measurement system is essential economic infrastructure for creating markets and trade internally but developed nations to all intents and purposes have a mature system that largely addresses day to day measurement needs and if it is working as it should, life goes on generally unaware of the surrounding metrological web. However, most developed nations have also quite correctly identified a very strong strategic link between economic competitiveness and measurement capability. The further development of their measurement systems has been, sometimes explicitly and rightly in the particular national interest, directed towards gaining advantages in trade, innovation, technical capabilities, industrial development, military operations and capabilities and other items of strategic national interest. It is self evident that the delegates to the CGPM are therefore not pure representatives of disinterested scientific measurement, and questions such as those of accountability, independence, transparency, succession and interests of its powerful administrative committee, the CIPM need continual, open scrutiny. Note that CIPM is formally the author of these strategic reports to CGPM. The deep questions of conflict of interest in the halls of global metrology within the wider political and economic sphere have not been considered. They are essential questions and should be asked regularly. For global measurement, trust is the global currency. This writer has no answer. He had in fact hoped to find the beginnings of such somewhere in the three strategic reviews of the future for global measurement needs.

In addition to the three big trends discussed above, there are two other issues that deserve far more prominence in any strategic discussion of the global measurement system. They are as follows:

Accreditation, transparency, trust and accountability

Accreditation is the process of demonstrating real-world competence to an independent and knowledgeable third party authority that enjoys the confidence of the measurement using public. It is the key link in the chains of trust that enable the modern measurement system to work. Modern measurement is highly technical and lacks transparency. Trust is a highly delicate flower, easily trampled and restored only with difficulty. Yet on it our world depends [19]. It is surprising that most NMIs—and also the Treaty—have historically been unenthusiastic about the application of the principles of accreditation to themselves. The first accreditation organisation, the Australian National Association of Testing Authorities (NATA) was formed in 1947 and became a model, with national and cultural differences, for the evolution of such organisations. NATA's history wryly notes that the notion that testing standards were themselves subject to examination was then a novel one. In some quarters it still is. It is perhaps notable that NATA's governing Council had included, since the 1950's, the Royal Australian Chemical Institute (RACI) and was accrediting chemical testing laboratories two decades before the (thermodynamic) mole was included in the SI and half a century before any attempt by the Treaty organisations to implement that decision.

In 2006, NATA spun off a separate subsidiary to undertake the proficiency testing services it had always provided and today there are specialised organisations skilled in the design and undertaking of measurement intercomparisons at any level. Accreditation agencies now accredit the competence of providers of proficiency testing schemes, just as they also accredit producers of certified reference materials. There is also the International Laboratory Accreditation Cooperation (ILAC) and regional analogues. Accreditation of themselves did come onto the agenda of NMIs until the 1990s. Even today, accreditation is viewed with suspicion in some halls of metrology. If there is something wrong with current accreditation practice, the solution is obvious: help to fix it. But of one thing, there can be no doubt. Global metrology needs credible, open, transparent accreditation processes, most especially at the very highest levels. It cannot function without them. The complexity of modern science and technology require it. This also is a matter of vital importance and I mention it to give due acknowledgement: it is an issue that is to some extent being addressed. There exist NMIs that not only have a full appropriate accreditation but are also accredited for the provision of proficiency testing. I congratulate them. It has taken half a century and is another example of an opportunity for leadership foregone due to systemic institutional and cultural factors.

The fixing of physical constants and the future of science

There is also a strategic question of another kind for which this writer has no answer. That it has not been openly addressed, appropriate risk analysis undertaken and insurance put in place must be a matter of deep concern. The declared technical strategy of the Treaty is to create so far as possible, definitions of base units in terms of fundamental constants of nature, such as Planck's constant, Boltzmann's constant, the universal gravitational constant, the speed of light, elementary charge, the masses of the proton and electron and so forth. We believe them to be the most constant things we currently know of and they may seem to be ideal as metrological anchors. Included in these fundamental constants is the Avogadro "constant", referred to in Part one of this discussion.

The pre-eminent authority on the values of the constants is CODATA, the Committee on Data for Science and Technology, an interdisciplinary expert committee created in 1966 by the International Council for Science (ICSU). It is not formally part of the Treaty but the close linkage of the SI units with the physical constants is well recognised and there is close cooperation with the Treaty organisations. The process being followed is for the Treaty to wait until a relevant constant is known with sufficiently less uncertainty than the current means of realising the relevant unit(s). The constant may then be fixed by conventional definition and then may be used to realise the now redefined unit(s), in a manner similar to that described previously for intrinsic standards. Note that the constant is defined as constant and its value defined exactly, without uncertainty. For example, this was done for the speed of light in 1983. From that date, the speed of light cannot change. If it does, by the definitions of our measurement units, we cannot notice it. That is a significant downside to this procedure.

No empirical test is possible of hypotheses that the constants so defined are not in fact constant. Any such test will be an exercise in circular reasoning. Such hypotheses are not wild and crazy. They have been seriously proposed by Nobel winners [20] and speculation is not unusual that the constants of physics that we know are phenomena localised in space–time [4, 8, 9, 21–24]. We have only been measuring them in the vicinity of the earth for a century or so and those measurements point to either variability or alarmingly frequent episodes of significant systematic error [4–8]. Variability of the fundamental constants is becoming no longer a testable proposition. Jacob Bronowski once noted that knowledge is a venture at the edge of uncertainty. The constants of physics are the cornerstones of physical science as we now know it and they are heavily interrelated and coupled by the equations of physics as currently known. By defining them as beyond empirical test are we blindfolding science to the possibility of change? Are we condemning our science and technology to stasis? I do not know the answer but it is a very large risk with large consequences for the future of the scientific enterprise. History tells us to be wary of science by definition. Nor has the Treaty been a good judge of the dynamism of science and technology. It is a prudent principle of practical measurement system design that base units should be chosen, contra the Treaty strategy, with independence and minimal coupling in mind—perhaps by focussing instead on direct elemental exemplars of the specific quantities of interest. That way, errors may be isolated and problems diagnosed. If everything is interconnected, a problem in one area infects the whole or worse, the problem becomes undetectable with all anomalies explained away as experimental errors. It is entirely possible that the future of science might depend on our measurement units being as independent of each other as possible—the direct opposite of the Treaty strategy. At the very least, metrologically independent monitoring on a permanent basis of the "fixed" constants is a very necessary strategic counterpart to fixing the constants. Without it, we have no "epistemic insurance" and we are as much the captives of our current assumptions as the medieval schoolmen were of theirs. As Bronowski put it so memorably, kneeling in the pond at Auschwitz, "think it possible you may be mistaken".

Conclusion 1: chemical measurement—where do we go from here?

In summary, then in the three strategic reviews of the future of the Treaty of the Metre, we have a distressing portrait of a dysfunctional institution, casting far and wide for relevance, revered for past glories but constitutionally quite unable to address past mistakes, let alone to meet the global measurement challenges of the future. These are classic symptoms of what economist Mancur Olsen concisely described as institutional sclerosis [25, 26]. The chance of this institution leading the chemical measurement community to the metrological Promised Land is precisely zero. It is deeply regrettable but we should face facts and get on with it.

The first and most vital question for chemical measurement is that of units [27]. It has long been a maxim of trade measurement that who controls the instrument, controls the transaction. But on the larger level, who controls the units on the scales of those instruments controls the very kinds of transactions that are possible. We are paying an unknown but assuredly large cost in opportunities foregone and confusions fostered by the dangerous and avoidable circumstance of two moles for two different quantities.

In one sense and it is significant, the solution for chemical measurement itself is trivial and involves a simple change in linguistic usage. All we need is a new word to describe the chemists' mole and the quantity for which it is a unit—a number of identified things. Chemistry is perfectly competent to do this without the permission of the CIPM. The term "mole" has been thoroughly debased and linguistically debauched and is nowadays unusable as a means of clearly communicating measurement results. We need a new term for an Avogadro number of things that communicates well and clearly to its audience that it is basically and essentially just that: a number of things. It must not be able to be confused with the thermodynamic artifice called "amount of substance". If we can do that, we can indeed get on with things.

Clearing up the semantic confusions may well have much farther reaching advantages by enabling a clearer view of the essentials of chemical measurements and so allow calm and measured consideration of the many real and practical options available to securely anchor and communicate their results. A frank and open discussion is necessary for this to be possible.

Conclusion 2: the institutional problem

The institutional problem is more difficult and I return to the theme of the introduction of Part 1 of this discussion concerning the central and essential symmetries between our economic world and our metrological world. The Treaty of the Metre was intended to enable world trade. It was spectacularly successful in its time, well over a century ago. George Soros [28] argues that the recent global financial crisis was but one of an evolving set of consequences of a slow breakdown, over decades, of the institutions for global financial coordination based on the sovereignty of the nation state. There are international agreements and there may be cooperation among regulators, but the ultimate source of authority is the nation state, just as it is in that quintessential instrument of economic coordination, the Treaty of the Metre. Soros' point was that there is an essential instability or lack of robustness under stress and that once trust is broken, it becomes impossible to repair. There is a self reinforcing spiral of distrust, at the same time diminishing whatever benefits may come from cooperation. These are also perfect conditions for Gresham's Law to rule, driving out both good money and good measure with equanimity. When it all comes down to it, governments are primarily concerned with their own economies and without globally accountable coordination mechanisms there is an ineluctable logic: financial protectionism is a clear and present danger to the world economy. There is also a clear and present danger on the other side of this symmetry, metrological protectionism—sometimes called technical barriers to trade. The time has come to consider whether the Treaty, venerable though it be, is still appropriate to the global needs of measurement in the 21st century.

Any such consideration needs to bear in mind that my own criticisms notwithstanding, NMIs are real, substantial assets with real capabilities of inestimable benefit to their respective nation states, just as the European Union's Institute for Reference Materials and Measurements is central to that Union and the technical capabilities of the International Bureau of Weights and Measures are to the global community.

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