

The Expanding Role of National Metrology Institutes in the Quantum Era

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Emerging quantum technologies pose new measurement challenges, but also offer previously unknown measurement solutions. National Metrology Institutes are playing a leading role in this fast evolving world.

Either Lord Kelvin, the inventor of the absolute temperature scale, or Peter Drucker, the man who invented modern business management, may have coined the phrase, “If you cannot measure it, you cannot improve it.” The varying attribution of this quote only emphasizes the pervasive nature of measurement in society and our daily life.

Metrology has often been both the motivation for and a direct beneficiary of ground-breaking discoveries. The Josephson and the quantum Hall effect provide the basis for the realization of electrical units. Rabi and Ramsey spectroscopy methods are essential to the operation of hydrogen maser and other atomic clocks. The invention of lasers led to even more accurate length metrology. Frequency standards now rely on ion and cold atom trap techniques, frequency combs and methods to manipulate the quantum state of matter.

These very same Nobel-Prize-winning precision metrology techniques have become the foundation for the rise in quantum technologies we are witnessing today. There is an intimate connection between advances in metrology and quantum technology, which is epitomized in the 2012 Nobel Prize awarded to David Wineland and Serge Haroche for their work that “enables measuring and manipulation of individual quantum systems” of matter and light as “the first steps towards the quantum computer, and the development of extremely accurate optical clocks.”¹

Trapped ions are presently one of the leading platforms for quantum computing, where qubits are encoded in quantum states of ions and manipulated by sequences of microwave or light pulses in much the same way as in atomic clocks (Figure 1). Another leading approach for quantum computing is based on superconducting qubits, which make use of Josephson junctions that are commonly used in the realization of voltage standards, albeit in a different implementation.

Until the redefinition of the International System of Units (SI) on the 20th of May 2019, the world of physical measurements was very comfortably organized for National Metrology Institutes (NMIs). The core NMI function was to be the guardians of practical standard realizations of the SI units to which all measurements had to refer to; this is known as traceability. The primary standards themselves took various forms, ranging from the low-tech international prototype of the kilogram² — essentially a chunk of precious metal alloy kept in a safe — or a fragile glass vessel containing water and ice to realize the kelvin to sophisticated atomic clocks used to define the second. The tick of our watches, our bathroom scales and our underarm thermometers were all referenced to these primary standards through a long uninterrupted chain of calibrations. NMIs sat at the top holding the traceability chain in their capable hands. The world worked in absolute harmony.

Redefining the world’s measurement system was in many ways a turning point for humanity, and certainly for NMIs. It is fair to say that this feat was achieved largely as a result of quantum measurements, such as that of the Planck constant for the redefinition of the kilogram.

For many years before the redefinition, scientists had measured fundamental constants in terms of the old units very accurately. They also ascertained the temporal invariance^{3,4} and universality^{5,6} of fundamental constants. The redefinition fixed these constants at their best known values to avoid a change in the results of measurements from before and after the redefinition. These fixed-value constants were then used to define the SI units. So, no-one should have noticed the transition: your tea kettle didn’t suddenly boil at a different temperature, and if your bathroom scale showed that you gained weight overnight, well, metrology was not to blame.

Now that all base units are defined in terms of fundamental constants and can thus — at least in principle — be realized anytime and anywhere, rather than through a measurement chain leading back to unique physical artefacts, who holds the traceability chains?

Quantum technologies enable the realization of high-precision standards both within laboratories and in the form of miniaturized, intrinsically accurate and quantum-referenced sensors. Combined with the new pathways for traceability opened up by the SI redefinition, they pose both an exciting challenge and a tremendous opportunity for NMIs.

With the redefinition, the SI units could in principle be realized outside NMIs. Now with recent advances in quantum technology, they can be in practice. Technology that originated from NMIs is increasingly becoming commercially available, enabling the realization of quantum standards outside the well-controlled NMI premises, for example, on the factory floor or close to the end-user. Inspired by their success in miniaturizing an atomic clock to a chip-scale version the size of a grain of rice, the National Institute of Standards and Technology (NIST) in the United States embarked on a sweeping “NIST on a Chip”⁷ programme to create small, deployable quantum sensors (Figure 2) to provide precision metrology at point-of-use, reducing the need for equipment to be sent to NIST for calibration.

Examples at NIST and other NMIs include microwave and optical atomic frequency standards⁸ equipped with compact comb technology for frequency transfer, Josephson voltage and quantum Hall resistance standards⁹ mounted on continuously operated cryocoolers, miniature Kibble balances to realize the kilogram and nanophotonic or shot-noise thermometers. These deployable quantum standards can dramatically shorten the calibration chains enabling more accurate end products. They are designed for easy operation so that their use does not require oversight by highly skilled metrologists.

The exciting prospect of diversified traceability ought not to result in measurement anarchy, and there will be a growing need for NMIs to develop relevant, increasingly automated measurement procedures and to oversee their correct implementation to ensure accurate calibration with the quantum standards at the point of use. Furthermore, designing, building and operating quantum standards remains a complex and demanding procedure. Things can go wrong leading potentially to incorrect operation, which — in the absence of a ‘classical’ traceability route — might not be obvious. To reliably ensure correct referencing, there will probably still be a need for a certain level of comparisons between complementary models and realizations, also on an international scale. In this way, NMIs can continue to play an important role by providing a worldwide quality-ensuring metrology network.

In the process of exploring and applying quantum effects for the benefit of metrology, NMIs around the world have gained immense expertise in wider quantum technologies. In many cases, this has paved the way for applications, such as relativistic geodesy¹⁰ and dark matter detection.¹¹ NMIs increasingly apply their capability to support responsible quantum innovation and industrialization, in particular by providing competent, independent and unbiased test and evaluation at the materials, component, device and system level — in some cases including evaluation of protocols and software.

Today such tests are applied in the domain of quantum communications, in particular quantum key distribution, the security of which crucially depends on the ability to generate and detect photons one at a time, something that optical metrologists can quantify in SI-traceable ways.¹² Relevant tests and procedures for the characterization of optical components for use in quantum key distribution

systems have already been standardized.¹³ Quantum random number generation is another rapidly maturing technology, which relies on the fundamental unpredictability of quantum processes.¹⁴ NMIs contribute to the development of tools and standards for statistical tests of randomness, entropy estimation and security of the generated random bits, and may in the future operate verifiable quantum-based random number beacons as a public utility.

Other less mature technologies, such as quantum computing, also require characterization, benchmarking and evaluation — both platform-specific and agnostic — to inform development and prioritize investment. Reliable characterization of components is furthermore important to help establish technological supply chains: properties of, for example, trapped ion or superconducting quantum processor chips need to be well defined to build more complex systems out of these core components. Work to develop and provide such hardware and software testing is underway at some NMIs^{15,16}, and the first standard describing the common vocabulary of quantum computing terms is under development. Further coordination of standardization activities between NMIs is important to ensure efficiency, a consistent approach and impartiality. On a European level, the first attempt for a common framework for standardization of quantum technologies is being developed.¹⁷

Despite its change in recent years, and most notably the 2019 redefinition, the SI is still a work in progress. Further evolution of the measurement system is going hand in hand with advances in quantum technologies.

One example of ongoing research is towards the direct realization of the ampere through the transfer of a single electron at a time with a high repetition rate instead of through Ohm's law. This is achieved by single-electron pumps, which currently lack the required accuracy or speed.^{18,19} Such a direct realization of the ampere with sufficient accuracy would open the way for the closure of the quantum electrical triangle — the ultimate consistency check between the electrical units. Moreover, the ability to deterministically control individual electrons may give rise to a new technology, single-electron quantum optics.²⁰

Another exciting proposal is to realize the ampere in a way similar to the voltage standard, which relies on voltage quantization in microwave-irradiated Josephson junctions. It was theoretically predicted²¹ that in narrow superconducting wires, which experience quantum phase slip, the current must also be quantized as a consequence of the fundamental charge–phase duality in superconductors. Because the Josephson effect is exact⁵ in terms of the relation between microwave frequency and voltage, the expectation is that the dual effect, which is relevant for the proposed realization of the ampere, will be exact in terms of the relation between frequency and current. Conversely, quantum phase slip junctions can be used as interferometric charge sensors and in alternative qubits.²²

Another transformation of the SI is also in the cards. Ironically, the unit that can be realized most accurately — the second — is due for imminent redefinition.²³ Advances in quantum technology have led to realizations of the second using optical atomic transitions with much lower estimated systematic uncertainty and higher stability than the present definition based on microwave transition in the hyperfine split ground state of caesium. Ultimately, a measurement cannot be more accurate than the standard, and this is currently limited by the microwave atomic clocks. Applications that will benefit from the redefinition of the second are those that directly refer to the time unit, in particular communications and navigation.

Last but not least, quantum phenomena, such as entanglement and squeezing, provide a path towards even greater measurement precision and speed. Compared to quantum sensors using

ensembles of independent particles, which are limited by the standard quantum limit, those using entanglement allows one to consider the particles as a single entity, which leads to shorter measurement times or an improved uncertainty down to the ultimate Heisenberg limit. In some cases, entanglement may be the only option to improve uncertainty because it enables higher precision using fewer particles, which is especially important in cases where it is impractical to increase particle density such as when measuring light-sensitive samples.

Although the standard quantum limit has been beaten in a number of physical systems, this was achieved with small entangled ensembles. In effect, the achieved sensitivity in many cases was no better than in optimized or larger systems without entanglement.²⁴ Decoherence in entangled ensembles is a serious obstacle, similar to the challenge it poses for quantum computing, and at present better results have been achieved by using a very large number of independent measurements. Understanding and mitigating decoherence will lead to breakthroughs in both quantum technology and measurement science.

The quantum era is creating a sense of urgency for NMIs to respond to their country's needs to be competitive. Not only are NMIs using quantum advantages to improve the measurements they already offer, but they must also devise reliable ways to make completely new measurements of novel quantities like entanglement, coherence and exotic states of light.

In addition, NMIs are increasingly asked to fill gaps to support the quantum economy, which is growing concurrent with the science itself. They are making more measurements that are disconnected from the SI to respond to such unusual questions as “how quantum is a quantum computer”, and to take a more active role in the development of documentary standards, which — among others — define terminology, establish specifications and describe test methods. NMIs are focusing more and more on research to accelerate the development of quantum technology and of non-traditional services, such as quantum random number generation. The earliest benefits of quantum standards will be reaped by the world's smaller NMIs, which will now have access to measurement capabilities they would not be able to afford otherwise.

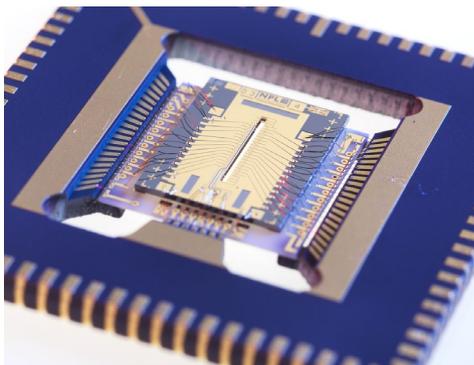


Figure 1. A microfabricated 3D ion trap. Such ion traps²⁵ can be used in quantum sensors, clocks, computers or simulators. Credit: NPL.

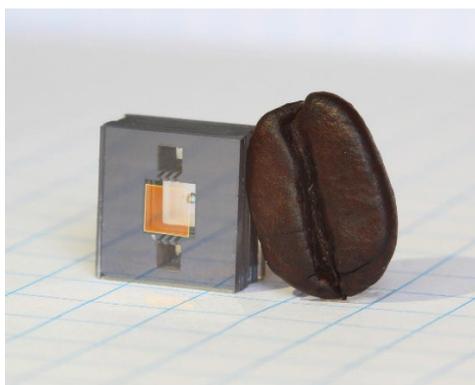


Figure 2. **Compact atomic clock vapour cell.** NIST's latest generation compact optical clock vapour cell, shown beside a coffee bean, is about a hundred times more stable and accurate than their original chip-scale microwave clock. Credit: Hummon/NIST.

Competing interests.

The authors declare no competing interests.

¹ Scientific Background on the Nobel Prize in Physics 2012: Measuring and Manipulating Individual Quantum Systems https://www.nobelprize.org/uploads/2018/06/advanced-physicsprize2012_02.pdf

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