QUANTIFYING OUR WORLD

BY DAVID J. LOCKWOOD AND NELSON L. ROWELL

Behind virtually everything that the public uses and consumes is the science of metrology, which is constantly evolving with society's needs. In this science, we measure physical quantities related to everyday experience. If you have ever been late for a meeting, had to run to work, go to the gym or turn on the air conditioning, you have experienced the results of the work of metrologists: time, distance, weight and temperature, are all studied.

Take time, for instance. Instead of being related to the size of the earth as it once was, the metre is now more accurately defined as how far light travels in a certain amount of time. Since the speed of light is a fundamental constant, it will not change based on environmental factors. A second of time—central to most aspects of life—is defined in terms of an atomic transition in cesium. However, as our measurement capabilities improve and are transformed, the methods of realizing the units also change. In some cases, the changes are revolutionary as they were for the Josephson volt and the quantum Hall standard for resistance. Normally, such changes in how the units are defined are not something that the general public would notice, but, ultimately, it does affect everyone.

Satellites sensing the environment, must accurately measure how much sunlight we catch to gauge its influence on global warming. Stock exchanges must time-stamp their trades with increasing accuracy. The Toronto Stock Exchange recently asked the National Research Council (NRC) for direct access to its detailed time signal—based on atomic clocks—so they can more precisely time-stamp their increasingly rapid transaction rates.

Perhaps the most visible example of the work metrologists perform is in the form of a 1965 request from then Prime Minister Lester Pearson, who entrusted NRC with the responsibility of establishing colour specifications for Canada's national flag. Today, Canada's red is a source of international pride that can withstand the tests of the elements.

SUMMARY

The science of metrology is constantly evolving to meet the physical needs of society. Over the past century NRC has led the way in many areas of primary metrology, which have benefitted Canadian society considerably – and will continue to do so.

Metrology is also critical to economic and industrial development. Impact studies indicate that it lowers transaction costs, contributes to energy conservation, increases research and development (R&D) efficiency and product quality, and enables new markets. Even though most never directly see the impact of this research directly, the financial return on the research investment is anywhere from 5 to 100 times. In other words, it literally pays to be precise!

NRC began expanding its metrology activities in the 1930s [1], and is now home to one of the world's most respected standards laboratories. Almost from its inception, NRC has played the role of Canada's highest-level metrology institution, and over the years has become one of the global leaders in measurement science. Most countries have their own National Metrology Institutes (NMIs), with the international coordinating body for such high-level metrology being at the Bureau International des Poids et Mesures (BIPM) in France.

At NRC, we ensure that Canada's measurements can be traced back to the International System of Units (SI), through our own independent realization of the units. This protocol is common to most countries and intercomparison establishes the level of equivalence among national measurement systems.

RECALIBRATING MEASUREMENTS

The SI comprises seven base units (see Fig. 1a and Table 1): metre (m), kilogram (kg), second (s), ampere (A), kelvin (K), candela (cd) and mole (mol), all of which need to be stable and realizable everywhere. As long ago as 1900, Max Planck noted that, if based on fundamental constants of nature, the units would "necessarily retain their validity for all times and cultures, even extraterrestrial and nonhuman." Although he could not have foreseen the changes that now drive the redefinition of some units, he was quite correct—prescient even—in his assertion.

It is now likely that in 2018, countries around the world will agree to changes in the definitions of the SI base units. It is proposed that the kilogram, ampere, kelvin and

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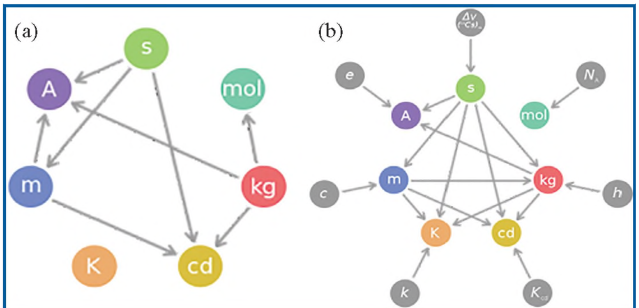

Fig. 1 (a) The diagram depicts the current SI in 2016. The arrows show the dependence of base unit definitions on other base units (for example, the metre is defined in terms of the distance travelled by light in a specific fraction of a second). For definition of units see Table 1. (b) Proposed SI for possible adoption in 2018. The dependence of base unit definitions is on physical constants with fixed numerical values and on other base units that are derived from the same set of constants.

mole be redefined by choosing exact numerical values for, respectively, the Planck constant, the elementary charge, the Boltzmann constant and the Avogadro constant (see Fig. 1b and Table 1). In this endeavour, NRC scientists provided significant contributions and/or leadership to the development of the new kilogram, kelvin and mole.

NEW KILOGRAM

For 126 years, *Le Grand K*, a platinum and iridium cylinder housed at BIPM in Paris (see Fig. 2), has defined the kilogram, being the only SI unit remaining based on a physical object.

Since the cylinders were manufactured in 1889, mass differences as large as 50 micrograms have been detected between the *Le Grand K* and its six official copies. Such variations are certainly within present measurement resolution, and cast into doubt the stability of the mass of *Le Grand K*, and hence that of the international mass unit. As a result, it was proposed that the standard kilogram be defined not in terms of a physical artifact, but through a physical experiment, relating the kilogram to the value of the Planck constant. In this new definition, the kilogram will also be dependent on the second and the metre.

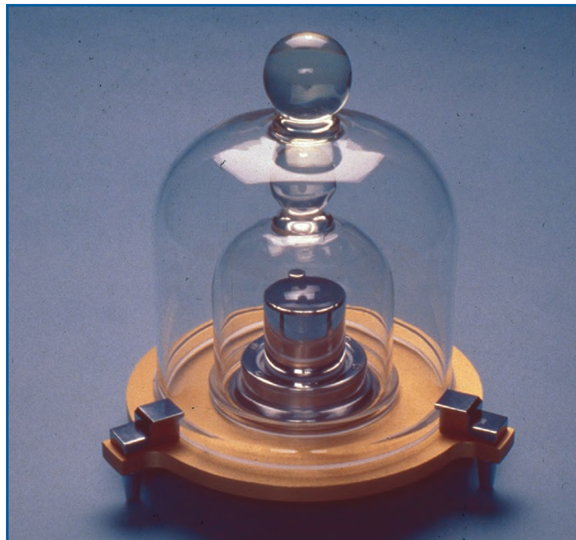

Fig. 2 Nested within several bell jars, rarely handled and stored in a controlled environment secure in a vault near Paris, *Le Grand K* is the artifact that presently defines the official SI unit of mass.

Counting atoms, as in the Avogadro Project [2], and weighing using watt balances [3] are the two distinct physical methods proposed to establish a mass unit that is not based on an artifact. It is required that both methods be so precise that their measurement uncertainties are less than 20 parts per billion (ppb).

In the international Avogadro Project, NRC has made a significant contribution by establishing the relative isotope ratios

TABLE 1

PHYSICAL CONSTANTS AND BASE UNITS EMPLOYED IN THE CURRENT AND PROPOSED SI.

Physical constants		Base units		
Constant	Symbol	SI quantity	Unit	Symbol
Velocity of light	c	Length	metre	m
Planck constant	h	Mass	kilogram	kg
Hyperfine transition frequency in cesium	Δν (Cs)	Time	second	s
Elementary electric charge	e	Current	ampere	A
Boltzmann constant	k	Temperature	kelvin	K
Luminous efficacy	K_{cd}	Light	candela	cd
Avogadro constant	N_A	Molecular weight	mole	mol

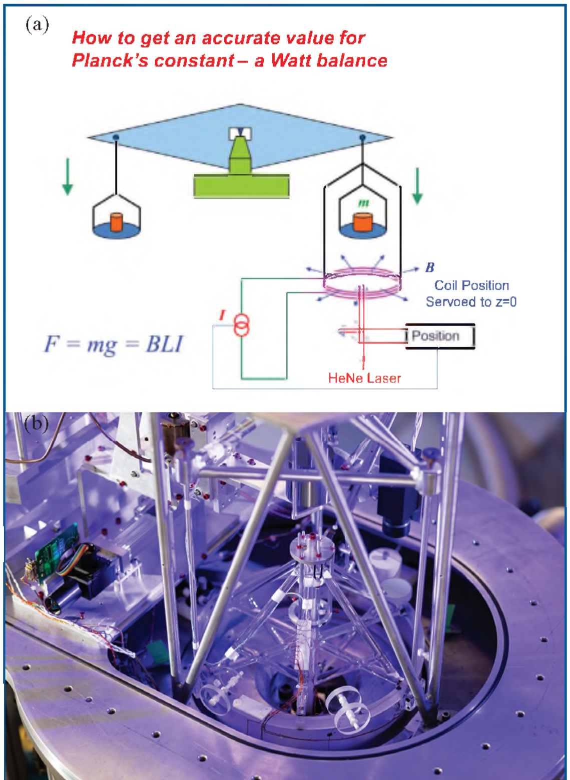

Fig. 3 NRC has recently completed a critical experiment – measuring the Planck constant to high accuracy using a watt balance, such that the measurement uncertainty is now below 14 ppb. The results are crucial to the redefinition of the SI kilogram. (a) In the upper panel, above, is a schematic of the watt balance in which the gravitational force due to the presence of a mass, *m*, is shown balanced by the electromagnetic force caused by the current through a coil. (b) In the lower panel, above, is a photograph of the NRC watt balance, with its vacuum cover removed.

in the silicon spheres nominally composed of a single isotope (mass 28), used in the atom-counting measurements of this project. Accurate knowledge of the trace amounts of the other isotopes provided by NRC allowed the Avogadro Project team to improve their value for Avogadro's constant, which they converted into a value for the Planck constant that was more accurate than their previous one.

A watt balance is used to produce a value for Planck's constant by weighing a test mass calibrated against an electromagnetic force (see Fig. 3a). NRC's metrology laboratory in Ottawa has the world-leading watt balance experiment (See Fig. 3b), presently providing values for the Planck constant with the lowest uncertainty ($<$ 15 ppb) of any such experiments. The NRC team has continually reduced the uncertainties in their results by analyzing and lowering systematic uncertainties. Currently, and significantly, NRC's results have the lowest uncertainties.

In a 2014-15 evaluation of NRC's programs, the report stated that other NMIs recognized NRC as "having made a noteworthy contribution to key metrology research developments, specifically the redefinition of the kilogram. Using experiments based on the watt balance, NRC has been able to achieve the most precise determination of the Planck constant to date." As stated by one international NMI interviewee, "unequivocally, this has been a major contribution to fundamental metrology." In recognition of its expertise in metrology, NRC has recently been invited to join the Consultative Committee for Units.

While the idea of redefining the kilogram in terms of electrical quantities has been around for some time, the accuracy and stability of electrical measurements has improved tremendously over the years, taking advantage of quantum phenomena in the Josephson and von Klitzing effects. Because electrical quantities are now based on fundamental constants, we know they are very accurate and stable. Such advances in measurement science allow us to build a mass unit based on electrical quantities, so that we can retire the kilogram artifact [4].

NEW KELVIN

Most practical temperature measurement around the world is based on a defined scale, the International Temperature Scale of 1990 (ITS-90), which relies on the best temperature values at fixed points (e.g., melting or freezing). This approach to evaluating temperature now has a number of issues. We know that, with better measurement methods now available, the temperature values derived using ITS-90 and the actual (thermodynamic) temperatures are not exactly the same. While these differences would not be noticed by—nor likely all that important to—the average person, some more specialized applications do need to use exceptionally accurate temperatures, more so than those afforded by ITS-90, especially away from the fixed points.

As an example of calibration accuracy and its significance to society, we know that climate-monitoring satellites are intended to provide us with actual (thermodynamic) temperature quite accurately in the environmental range between approximately -70 and 50 degrees Celsius. As the lower part of this range is one of the places where there are significant deviations between ITS-90 and thermodynamic temperature, measurements referenced to calibration devices internal to the satellites using ITS-90 have to be corrected before the results are used, for example, in physical models.

The definition of the kelvin is undergoing a fundamental change. Rather than using the triple point of water to fix the temperature scale, it will be based on a fixed value for the Boltzmann constant; however, the temperature at the triple point of water will remain the same [5]. NRC, through its mastery of primary thermometry, is now one of the world leaders in this area.

Another illustration of the importance of controlling calibration uncertainty was noted in radiometry and radiation thermometry several years ago with the controversy about the amount of sunlight (total solar irradiance) incident outside the atmosphere [6]. Over the years, beginning in the late 1970s, space-based measurements of solar irradiance were made on a continuous basis with a series of radiometric instruments. The results contained significant differences between the radiometers, generation to generation, due to a small but overlooked source of calibration uncertainty. This resulted in inter-instrument variances of a few watts per square metre, which, although only 0.3% of the total, were significant relative to the other radiation components that comprise the current global radiative energy imbalance. This particular calibration uncertainty was corrected with more accurate metrology, which will also be required to evaluate the reliability of the measurements in the long term.

TIME (THE SECOND)

Time measurement, the most accurate metrology, has always been based on the idea of an oscillator, e.g., as in the pendulum. Even atomic clocks measure the natural microwave oscillation of an atomic transition in cesium. From the 1950s onward, NRC metrologists were early innovators (see Fig. 4) of this type of technology [7,8,9], building some of the first – and finest – cesium clocks with high-quality frequency and time-measurement capabilities [10].

Today, although the precision of cesium clocks has been somewhat surpassed by optical frequency standards, the unit of time is still based on cesium standards. Nonetheless, we should still be aware that the present cesium atomic clocks have extremely low uncertainties (less than one part in 10^{16}). This amount is less than a nanosecond per century, so that if such a clock were running continuously, it would take about 100 million years to be out by a second. Further improvements in precision could, however, still be significant in various areas.

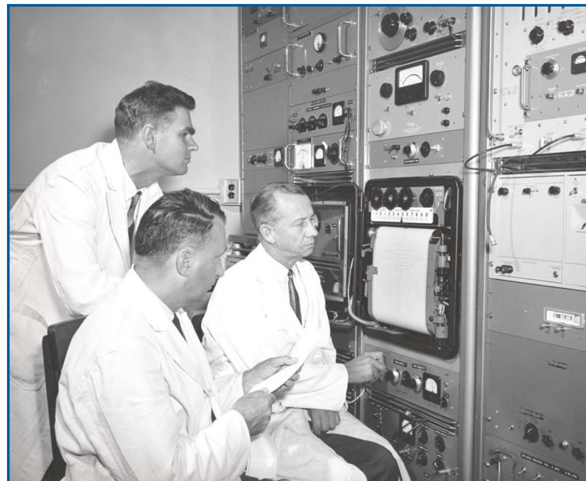

Fig. 4 In 1965, NRC employees Allan Mungall, Herman Daams and Ralph Bailey check out a chart recording of the Ramsay fringes originating from NRC's primary, atomic beam, cesium clock of the day.

CONCLUSION

Although its metrology programs are relatively small by international standards, NRC continues to be one of the world's top NMIs, and has contributed significantly to the developments leading toward the new SI. Over the past century NRC has led the way in many areas of primary metrology, which have benefitted Canadian society considerably—and will continue to do so. Perhaps, by that standard, we would need to revisit how we measure the size of metrology programs. If such a redefinition were to take place, NRC would no doubt be at the forefront, ready to tackle the challenge.

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