An introduction to the New SI

Sandra Knotts

Perkiomen Valley High School, Collegeville, Pennsylvania 19426

Peter J. Mohr

National Institute of Standards and Technology, Gaithersburg, Maryland 20899

William D. Phillips

National Institute of Standards and Technology Gaithersburg, Maryland 20899 and
University of Maryland, College Park, Maryland 20742

Abstract

Plans are underway to redefine the International System of Units (SI) around 2018. The New SI specifies the values of certain physical constants to define units. This article explains the New SI in a way that could be used to present it to high-school physics classes.
I. INTRODUCTION

Physical science is based on measurements, and the results of measurements are expressed in terms of units. For example, someone can measure the length of a table and report that it is 1.4 m long, where m stands for meters. This statement provides useful information to other people, because there is general agreement about what a meter is. In fact, there is a treaty among 55 nations, including the US, that says they agree on what the meter is. Not surprisingly, the treaty is called the Convention of the Meter, and it also specifies other units. According to the treaty, the International System of Units, known as the SI, is agreed to be the present day standard by which all participating member states set their units. Even though a majority of people in the US still use units such as inches and pounds, the official standards for these units are linked to the SI. For example, the US definition of the inch is that it is exactly 0.0254 m.

Although the practice of establishing standards for measurements dates back thousands of years, the Convention of the Meter was only established in 1875 with seventeen nations initially signing on, including the US. Incidentally, the anniversary of the signing, 20 May, is now known as World Metrology Day. The SI, established in 1960, is still more recent and is continuously evolving. In fact, it is anticipated that the definitions of measurement standards specified by the SI will undergo a substantial change in 2018. In the New SI, units are defined by assigning specific values to a set of physical constants. Despite the fact that the definitions will be changed, the effect on everyday measurements will be imperceptible. The purpose of this paper to describe the new version of the SI and show how units will be based on the new definitions.

II. THE DEFINING CONSTANTS

The concept of defining units by assigning values to physical constants requires some explanation. The previous example of a table that is 1.4 m long illustrates this idea. The fact that the table is 1.4 m long is determined by comparing its length to the length of an object that is 1 m long, in particular a meter stick. Now if through some natural disaster all of our meter sticks disappeared, we would have a problem determining lengths. However if the table survived the disaster, we would have a physical object by which we could now
define the meter. We could say the meter is the length standard so that if we measure the table it will come out to be 1.4 m long. In this way we’re taking a physical object, assigning a numerical value to its length, and this in turn determines the meter, the unit of length.

The definition of the new SI is based on this principle. By assigning a value to the result of a measurement of a property of nature, one can define the unit that is used to make the measurement. Unlike the table, which is a particular physical object, the properties of nature, or quantities that are actually used for the definitions, are expected to be unchanging and available to anybody with the appropriate measurement tools.

A. Frequency and time

The frequency standard for the SI is established by assigning a value to the frequency of a particular atomic transition. It is currently, and for a while in the New SI will continue to be, the frequency corresponding to the transition between the two hyperfine levels in the ground state of a cesium atom. Here frequency refers to the frequency of the electromagnetic radiation absorbed or emitted when the atom makes a transition between the two hyperfine levels. The value assigned to the frequency is 9 192 631 770 cycles per second, where the unit cycles per second is called hertz or Hz. This value, about 9 GHz (the G stands for \(10^9\)), is in the microwave frequency range, similar to kitchen microwave oven frequencies, which can be about 2.5 GHz.

Once this standard of frequency is defined, it is possible to determine other frequencies by comparison to this standard or determine a second by counting cycles of the frequency. There are commercial instruments that can count periodic cycles at this frequency. Since there are exactly 9 192 631 770 cycles of the radiation in a second, we can time one second by counting off that number of cycles of the standard frequency.

It is this latter possibility that gives the name to atomic clocks. The actual functioning of the cesium clock is as a frequency standard, but it can be used to measure time by counting cycles of electromagnetic radiation.
B. Velocity and length

Microwaves and light are forms of electromagnetic radiation that differ only in their frequencies. The frequency of light is roughly 500 THz (the T stands for $10^{12}$). Despite the difference in frequency between microwaves and light, all electromagnetic radiation travels at the same speed, even if it is measured by someone moving relative to the source of the radiation. This is the principle of Einstein’s theory of special relativity. This speed is just the velocity of light, denoted by $c$, which has an assigned value of $c = 299,792,458$ meters per second in both the current SI and the New SI. This provides a universal velocity standard to which other velocities may be compared.

At the same time this provides a standard for length in the SI. The wavelength of light, denoted by $\lambda$, is the distance between peaks of the electromagnetic radiation. For light traveling past a point in space, the number of wavelengths that go by in a second is the frequency, denoted by $f$, of the radiation. So the total distance traveled by light in one second is the wavelength times the number of wavelengths that pass a stationary point, or the wavelength times the frequency. This distance is just 299,792,458 m because the velocity of light is that many meters per second. This is expressed by the equation $\lambda f = c$. Because of this relationship, for light of a given frequency the wavelength will be a certain known length which can be used to determine the length of one meter. In practice, one way of doing this is by using an interferometer which allows distances to be determined by counting off wavelengths as the distance between two mirrors is changed.

C. Voltage and resistance

Modern measurements of electrical quantities are made using two quantum phenomena from condensed matter physics, namely the Josephson effect and the quantum Hall effect.

For measurements of voltage, the Josephson effect is used and yields a value in terms of an applied frequency (which is defined as described earlier) and the Josephson constant, denoted by $K_J$, which is about 484 THz/V. Resistance measurements are made with the quantum Hall effect and are expressed in terms of the von Klitzing constant, denoted by $R_K$, given by about 25 813 Ω, where the unit is ohms. Since voltage and resistance can be measured in terms of these two constants, it follows from Ohm’s law that current can also be
determined by measuring the voltage across a resistor of known resistance when the current flows through.

Presently, both the Josephson and von Klitzing constants are accurately, but not exactly, known. On the other hand, the measurements of voltage and resistance in terms of these constants can be made even more accurately than the constants themselves are presently known in SI units. In the New SI, these constants will for all practical purposes be exactly known. The values are assigned as described in the next section.

D. Charge and action

The unit of electrical charge, denoted by $e$, is the charge of a proton or the negative of the charge of an electron. It is approximately $e = 1.6 \times 10^{-19}$ C, where the unit is coulombs or C. In the New SI, the unit of charge is assigned an exact value.

The Planck constant, denoted by $h$, is a universal constant associated with quantum mechanics and is approximately $6.6 \times 10^{-34}$ J s. It has units of action, which is equivalent to energy multiplied by time. This constant has a number of roles in quantum physics. It is the constant of proportionality that gives the energy of a photon, a quantum of electromagnetic radiation, in terms of its frequency $f$; the energy of a photon is $E = hf$. The Planck constant is also the unit of angular momentum. The smallest angular momentum of an elementary particle such as the electron is $\hbar/4\pi$. It happens that in the present SI, action and angular momentum have the same units. The Planck constant also appears in the Heisenberg uncertainty relation. In the New SI, the Planck constant is assigned an exact value.

An additional role of the Planck constant is in the Josephson effect and the quantum Hall effect. Both the Josephson constant and the von Klitzing constants are simple functions of the unit electric charge and the Planck constant. The relations are $K_J = 2e/h$ and $R_K = \hbar/e^2$.

Since in the New SI, both the electric charge and the Planck constant are assigned exact values, this defines the units of charge C and action J s. As an additional consequence, because of the relation to the Josephson and von Klitzing constants, both of those constants are also exactly known, and electrical measurements as described in the previous section will give results in terms of exactly known constants.
The assigned values of $e$ and $h$ that will be used for the redefinition are not yet completely set. The exact values will depend on whatever relevant experimental information is available at the time of the redefinition.

E. Mass and power

In the SI, an important unit is the kilogram for mass. In the New SI, the mass of an object in kilograms can be determined from the units already defined. Once the unit of charge and the Planck constant are defined, electrical units in terms of the Josephson and von Klitzing constants are known, and this is enough to determine the mass of an object using these units and others previously defined.

The principle can be understood through a simple thought experiment to measure mass. Suppose we construct an apparatus consisting of an electric motor that can wind up a string that has a mass hanging at the end. If the motor is run to lift the mass, it will work against the force of gravity on the mass. The motor will exert a certain average power which is the increase in potential energy of the mass divided by the time it takes to lift it. The necessary power is proportional to the mass being lifted. The same average electrical power is consumed by the motor lifting the mass, which is the voltage times the current being supplied to the motor. Since these quantities can be measured with the electrical units already defined, the mass can be determined.

The local acceleration of gravity is also needed in order to know the force of gravity on the mass. It can be determined by dropping an object and measuring its acceleration with the time and velocity units already defined.

In this way, comparing mechanical power to electrical power, mass can be measured. The most precise way of doing this is using an apparatus called the watt balance, where the watt is the unit of power. The watt balance is essentially an electrical scale that measures mass by weighing it in the presence of gravity. To avoid friction, which would be a problem for the simple motor example mentioned, the watt balance makes the measurement in two steps. One step is the measurement of the current through a coil in a magnetic field that supports a mass with no motion, and the other step is the determination of the magnetic field by moving the coil through it and measuring the induced voltage on the coil. The result is a combination of electrical quantities that is equivalent to power, which is the source of
the name of the apparatus. Model watt balances are described by Quinn et al. and Chao et al.

Electrical power, the product $VI = VV'/R$, where the current is determined by measuring the voltage $V'$ across a resistor with resistance $R$ calibrated with the quantum Hall effect, is proportional to the combination $K^2 J R K = 4/h$. The electric charge cancels from this combination, so it does not need to be exactly known in order to measure mass. The mass determination depends only on $h$ and the time and length standards mentioned earlier. However, having $e$ also exact allows for separate measurement of both voltage and resistance.

Another method of determining mass in the New SI is to produce an object with a mass of one kilogram as a standard. This can accurately be done based on the fact that in the New SI, because the Planck constant is exact, the mass of one silicon-28 atom is known in kilograms with a precision of about 10 significant figures from experiments that measure the recoil of an atom when it absorbs a photon, for example. A spherical single crystal of these atoms can be made with the suitable number of atoms needed to make up one kilogram. The number of atoms in the spherical crystal is determined by the measured volume of the sphere and the measured average spacing between the atoms in the crystal structure. This provides a method of producing an object with a mass of one kilogram that is independent of the watt balance.

F. Amount of substance

The amount of stuff, or more precisely, amount of substance in the SI is just the number of items, atoms, molecules, etc., under consideration. The unit of amount of substance is the mole, which consists of approximately $6.02 \times 10^{23}$ items. In the New SI, this number is fixed by assigning an exact value to the Avogadro constant, denoted by $N_A$, which is defined to be that number of items per mole. As in the case of the elementary charge and the Planck constant, the exact number will be determined by the results of experiments done up to the time of the redefinition so that it is close to the number in the current SI.
G. Temperature

Temperature can be measured with a gas thermometer based on the ideal gas law: \( pv = nRT \). In this equation, \( p \) is the pressure of the gas in a container, \( v \) is the volume of the container, \( n \) is the number of moles of gas in the container, \( R \) is the ideal gas constant, and \( T \) is the temperature of the gas. One can imagine that the gas chamber is in contact with the object whose temperature is being measured, so the temperature of the gas will eventually be equal to the temperature to be measured. The temperature \( T \) of the gas may be found by determining the rest of the terms in the ideal gas law equation and solving for \( T \).

This can be done, based on the definitions already mentioned, as follows. The pressure \( p \) is force per unit area. A standard for force can be calibrated by comparison to the force of gravity on a known mass, and area is just length squared. The volume \( v \) is just length cubed. The number of moles \( n \) of gas in the chamber is the total number of atoms \( N \) divided by the Avogadro constant \( n = N/N_A \). This leaves the problem of determining the ideal gas constant \( R \), which is related to the Boltzmann constant \( k \) by \( R = N_A k \). In the New SI, the Boltzmann constant is one of the exactly defined constants, which means that \( R \) is also exactly known. So, using this definition, we get the temperature from the various other measured aspects of the gas thermometer.

Note that from the fact that \( nR = Nk \), it can be seen that the Avogadro constant is not necessary for such a measurement of temperature, although it provides a more convenient measure of the amount of gas than the number of atoms does.

The Boltzmann constant is approximately \( 1.38 \times 10^{-23} \text{ J/K} \), where K or kelvin is the unit of temperature in the SI. Evidently, the product \( kT \) has units of energy. In fact, other methods of measuring temperature also involve measuring energy and the combination \( kT \) is what is measured. In this sense, the Boltzmann constant is a conversion factor from energy to temperature, which gives a number for temperature which is easier to communicate than the energy would be.
H. Light

For light, the candela, abbreviated cd, is the unit of luminous intensity, which is the power emitted by a light source in a particular direction multiplied by a factor $K_{cd}$, which takes into account the sensitivity of the eye to various colors of light.

One candela is approximately the luminous intensity observed for a candle, where it gets its name. If the source has a luminous intensity that is the same in all directions, then the total luminous flux is $4\pi$ lumen.

In the New SI, the candela is defined by specifying that the factor $K_{cd}$ for green light at 540 THz is exactly 683 lumen per watt.

III. NEW SI

The previous sections should make it clear how the specification of the values of seven constants defines the New SI units. This is the basis for the New SI, which together with the definitions of the various units with special names, such as the Joule, in terms of the units defined by the constants, is sufficient to define the entire SI. The International Committee for Weights and Measures intends to propose a revision of the SI as follows:

The International System of Units, the SI, will be the system of units in which:

- the ground state hyperfine splitting frequency of the cesium 133 atom $\Delta\nu^{(133\text{Cs})}\text{hfs}$ is exactly 9 192 631 770 hertz,
- the speed of light in vacuum $c$ is exactly 299 792 458 meter per second,
- the Planck constant $h$ is exactly $6.626 \ldots \times 10^{-34}$ joule second,
- the elementary charge $e$ is exactly $1.602 \ldots \times 10^{-19}$ coulomb,
- the Boltzmann constant $k$ is exactly $1.380 \ldots \times 10^{-23}$ joule per mole,
- the Avogadro constant $N_A$ is exactly $6.022 \ldots \times 10^{23}$ reciprocal mole,
- the luminous efficacy $K_{cd}$ of monochromatic radiation of frequency $540 \times 10^{12}$ Hz is exactly 683 lumen per watt,
where the dots (…) will be replaced by additional digits some of which have yet to be
determined by experiments to be done up to the time of the redefinition. From then on, the
constants will be defined to be exactly those values.

IV. NEW SI VS. CURRENT SI

The essential change from the current SI to the New SI is in the definitions of the units. In the current SI, seven base units are defined by the following statements:

- The meter is the length of the path travelled by light in vacuum during a time interval of $\frac{1}{299\,792\,458}$ of a second.

- The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.

- The second is the duration of $9\,192\,631\,770$ periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom.

- The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to $2 \times 10^{-7}$ newton per meter of length.

- The kelvin, unit of thermodynamic temperature, is the fraction $\frac{1}{273.16}$ of the thermodynamic temperature of the triple point of water.

- 1. The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12; its symbol is “mol”.

  2. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.
• The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency $540 \times 10^{12}$ hertz and that has a radiant intensity in that direction of $1/683$ watt per steradian.

In the New SI, no units are singled out as base units. The concept of base units is a carryover from when the meter and kilogram were both defined in terms of metal objects. In the New SI, it is recognized that the definitions are not directly linked to the earlier base units in a one-to-one relationship. For example, in the New SI, the speed of light $c$ is given a particular value and that defines the combination of units m/s. Similarly, giving $h$ a particular value defines the combination J s or kg m$^2$/s. The defining constants provide definitions of enough combinations of units so that they are all uniquely determined.11

Although the forms of all of the definitions are different, some of the units are unchanged in the New SI. In particular, the meter, second, and candela are equivalent in the New and current SI. On the other hand, the kilogram, ampere, kelvin, and mole are defined differently. In fact, in the current SI, the kilogram is still the mass of a metal artifact kept in a vault near Paris, as it was first in 1889.

V. WHY CHANGE?

The New SI is a significant improvement over the current SI, which is the reason for changing. Some of the improvements are as follows.

The current definition of the kilogram, in terms of a metal artifact, is problematic, because the mass of the artifact is changing relative to the mass of similar copies. In addition, it needs to be washed before being used for measurements, and in that process, the mass also changes. These variations are larger than the uncertainty in the measurement of mass using a watt balance or a silicon crystal sphere for a comparison standard, so the New SI will allow for more reliable mass measurements.

Electrical measurements using the Josephson effect and the quantum Hall effect are more accurate than the Josephson and von Klitzing constant are currently known in terms of SI units. As a result, since 1990, electrical measurements have been made in terms of assigned values for these constants. The assigned values are not directly tied to the SI, so electrical measurements are not actually done in terms of SI units. With the exact specification of the
electric charge and Planck constant in the New SI, the Josephson and von Klitzing constants are well defined, and the results of electrical measurements will be given in actual SI units.

The new definition of the mole states the number of entities in a mole. In the current SI, the mole is the number of carbon atoms in 0.012 kg of carbon, but the actual number is not given, which is less clear.

For temperature, the kelvin is currently defined in terms of the triple point of water, that is the unique temperature at which water coexists as ice, liquid and vapor. However, this property of water depends on the purity and isotopic composition of the water used. The kelvin is better defined if linked to an exact numerical value of the Boltzmann constant $k$.

When expressed in terms of the units of the New SI, the values of many physical constants have smaller uncertainties, and some, besides the defining constants, are exact.

VI. CONCLUSION

It is expected that the SI will be redefined as described here approximately in 2018. The time for this to happen depends mainly on experiments that determine the value of the Planck constant being sufficiently accurate that the defined value in the New SI will be correct.

The New SI is another step in the improvements in measurement standards that have been happening over the millennia.

VII. TOPICS FOR FURTHER STUDY

Some topics related to the redefinition that could be the basis for further studies are:

- History of units.
- Determination of physical constants.
- Hyperfine splitting frequency.
- Interferometry.
- Josephson effect.
- Quantum Hall effect.
• Watt balance experiment.
• Crystal lattice spacing measurements.
• Atom recoil experiments.
• Temperature measurements.

1 http://www.bipm.org/ (2014).
2 http://www.bipm.org/en/si/ (2014).
3 I. M. Mills, P. J. Mohr, T. J. Quinn, B. N. Taylor, and E. R. Williams, Phil. Trans. R. Soc. A 369, 3907 (2011).
4 M. J. T. Milton, R. Davis, and N. Fletcher, Metrologia 51, R21 (2014).
5 D. B. Newell, Physics Today 67, 35 (2014).
6 P. J. Mohr and D. B. Newell, Am. J. Phys. 78, 338 (2010).
7 P. J. Mohr, B. N. Taylor, and D. B. Newell, Rev. Mod. Phys. 84, 1527 (2012).
8 T. Quinn, L. Quinn, and R. Davis, Physics Education 48, 601 (2013).
9 L. S. Chao, S. Schlamminger, D. B. Newell, J. R. Pratt, G. Sineriz, F. Seifert, A. Cao, and D. Haddad, Am. J. Phys. xx, xxx (2014).
10 http://www.bipm.org/utils/en/pdf/24_CGPM_Resolution_1.pdf (2011).
11 P. J. Mohr, Metrologia 45, 129 (2008).