Standard Weights and Measures

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We trace the evolution of standards for weights and measures from olden days to their modern scientific definitions. Even in the era of modern science, standards till recently used to be defined by artifacts. It is only in the last few decades that we have gone over to definitions based on fundamental constants of nature. This has made the standards universally reproducible. The present standards for time, length, and electrical units are all based on physical constants. The mass standard, represented by the prototype kilogram, is the only remaining artifact, but there are promising proposals to replace that in the near future.

Ever since humans started living in community settlements, day to day activities have required the adoption of a set of standards for weights and measures. For example, an everyday statement such as "I went to the market this morning and bought 2 kgs of vegetables; the market is 1 km away and it took me 15 mins to get there" uses the three standards of *mass, length,* and *time.* Without a common set of measures for these quantities, we would not be able to convey the quantitative meaning of this statement. The scientific study of such measures is called metrology and it is an important part of modern industrial societies. In most nations, standards for weights and measures are maintained by national institutions (such as the National Physical Laboratory in New Delhi) in coordination with similar bodies in other countries. The definitions and maintenance of standards are improving constantly with progress in science and technology.

In olden times, each local community had its own set of measures defined by arbitrary man-made artifacts. As long as inter-community trade was not common, this proved to be sufficient. Usually kings and chiefs used their power to set the standards to be employed in their territories. For example, the measure of length 'inch' was probably defined as the size of the thumb of a tribal chief and the length of his foot gave birth to a standard 'foot'. As trade and commerce increased it became necessary to introduce more global standards. In addition, with the rise of rationalism and modern science in 17th century Europe, the limitations of such arbitrary definitions soon became apparent. For instance, the results of controlled scientific experiments in different laboratories could not be compared unless all scientists agreed on a common set of standards. In this article, we will see the evolution of *rational* standards for time, length and mass, from those early days to their modern scientific definitions.

Consistent standards are best based on fundamental physical constants.

Modern standards have to satisfy several important requirements: they should be *invariant*, i.e. the definition should not change with time; they should be *reproducible*, i.e. it should be possible to make accurate and faithful copies of the original; they should be on a *human scale*, i.e. of a size useful for everyday purposes; and they should be *consistent* with physical laws, i.e. a minimum number of independent units should be defined and other units derived from these using known physical laws. As we will see below, it is only in recent times that these requirements have been met in a consistent manner. An important way to achieve these goals is to define standards based on fundamental constants of nature. This helps us get away from artifacts and makes the definition universal.

Time Standards

We start with standards for time. Time keeping is as old as the earth itself since all it requires is a periodic process. The rotation and revolution of the earth give rise to daily and yearly cycles, respectively, and this has been used by nature as a clock much before humans evolved. Many living organisms including humans show diurnal (24 hour) rhythms regulated by the sun and seasonal patterns that repeat annually. It is therefore natural that the earliest man-made clocks also relied on the sun (*Box* 1). One example is the sundial (see the picture on the cover and *Figure* 1). It consisted of a pointer and a calibrated plate, on which the pointer cast a moving shadow. Of course this works only when the sun is shining. The need to tell the time even when the sun was not out, such as on an overcast day or in the night, caused man to invent other clocks. In ancient Egypt, water clocks known as *clepsydras* were used. These were stone vessels with sloping sides that allowed water to drip at a constant rate from a small hole near the bottom. Markings on the inside surface indicated the passage of time as the water level reached them. While sundials were used during the day to divide the period from sunrise to sunset into twelve equal hours, water clocks were used from sunset to sunrise. However, this definition made the 'hours' of the day and night different, and also varying with the season as the length of the day changed. Other more accurate clocks were used for

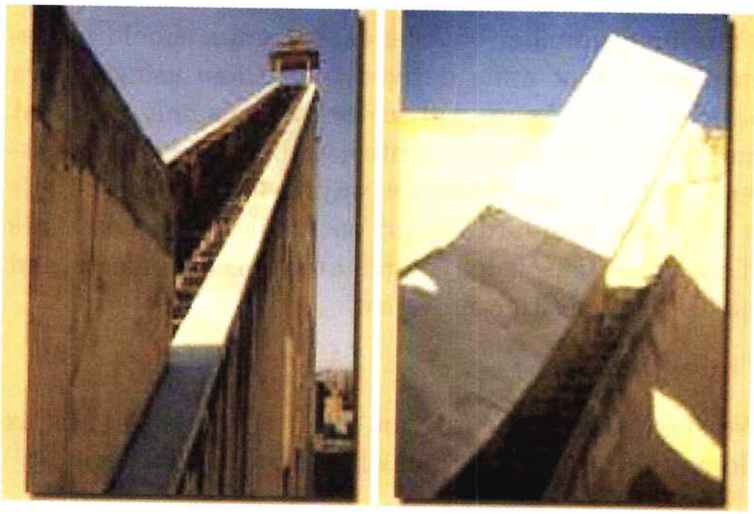

Figure 1. Sundial at Jaipur. The photographs are different views of the large equatorial sundial at the Jantar Mantar Astronomy Observatory. The left picture shows the 30 m high ramp (gnomon) whose shadow is cast on the scale. On the right is the end of the eastern scale in the late afternoon.

Box 1. A Brief History of Time-keeping

As mentioned in the text, the oldest clocks in the world are sundials. Many designs for sundials exist. They have evolved from simple designs of flat horizontal or vertical plates to more elaborate forms, which compensate for the motion of the sun in the sky during the course of the year. For example, one design has a bowl-shaped depression cut into a block of stone, with a central vertical gnomon (pointer) and scribed with sets of hour lines for different seasons. The Jantar Mantar observatory in Jaipur has more than 20 sundials, and the largest one is shown on the cover page and on p.46 in *Figure* 1.

The oldest clocks which did not rely on observation of celestial bodies were water clocks. They were designed to either drip water from a small hole or fill up at a steady rate. Elaborate mechanical accessories were added to regulate the rate of flow of water and display the time. But the inherent difficulty in controlling the flow of water led to other approaches for time keeping. The first mechanical clocks appeared in 14th century Italy, but they were not significantly more accurate. Accuracy improved only when the Dutch scientist Huygens made the first pendulum clock in 1656. Around 1675, Huygens also developed the balance wheel and spring assembly which is still found in mechanical wrist watches today. In the early 18th century, temperature compensation in pendulum clocks made them accurate to better than 1 second per day. John Harrison, a carpenter and self-taught clock-maker, refined temperature compensation techniques and added new methods of reducing friction. In 1761, he built a marine chronometer with a spring and balance wheel assembly that won the British government's 1714 prize (worth about Rs.10 crores in today's currency) offered to the first person to construct a clock capable of determining longitude to within half a degree at the end of a voyage from England to Jamaica. Harrison's chronometer kept time on board a rolling ship nearly as well as a pendulum clock on land, and was only 5.1 seconds slow after 81 days of rough sailing, about 10 times better than required.

The next improvement was the development of the nearly free pendulum at the end of the 19th century with an accuracy of one hundredth of a second per day. A very accurate free pendulum clock called the Shortt clock was demonstrated in 1921. It consisted of two pendulums, one a slave and the other a master. The slave pendulum gave the master pendulum gentle pushes needed to maintain its motion, and also drove the hands of the clock. This allowed the master pendulum to remain free from mechanical tasks that would disturb its regularity.

Time keeping was revolutionized by the development of quartz crystal clocks in the 1920s and 30s. Quartz is a piezoelectric material, meaning that it generates an electric field when mechanical stress is applied, and changes shape when an electric field is applied. By cutting the crystal suitably and applying an electric field, the crystal can be made to vibrate like a tuning fork at a constant frequency. The vibration produces a periodic electrical signal that can be used to operate an electronic display. Quartz crystal clocks are far superior to mechanical clocks because they have no moving parts to disturb their regular frequency. They dominate the commercial market due to their phenomenal accuracy and low cost. For less than Rs. 100, you can get a watch that is accurate to about 1 second per year! This has put many mechanical watch manufacturers out of business. Despite this success, quartz crystal clocks ultimately rely on a mechanical vibration whose frequency depends critically on the crystal's size and shape. Thus, no two crystals can be precisely alike and have exactly the same frequency. That is why they cannot be used as primary time standards and why atomic clocks are significantly more accurate.

measuring small intervals of time. Examples included candles marked in increments, oil lamps with marked reservoirs, hourglasses filled with sand, and small stone or metal mazes filled with incense that would burn at a certain rate.

Time measurements became significantly more accurate only with the use of the pendulum clock in the 17th century. Galileo had studied the pendulum as early as 1582, but the first pendulum clock was built by Huygens only in 1656. As we now know, the 'natural' period of the pendulum clock depends only on the length of the pendulum and the local value of g, the acceleration due to gravity [1]. Huygens' clock had an unprecedented error of less than 1 minute per day. Later refinements allowed him to reduce it to less than 10 seconds a day. While very accurate compared to previous clocks, pendulum clocks still showed significant variations because even a few degrees change in the ambient temperature could change the length of the pendulum due to thermal expansion. Therefore clever schemes were developed in the 18th and 19th centuries to keep the time period constant during the course of the year by compensating for seasonal changes in length. Pendulum clocks were also not reproducible from one place to another because of variations in the value of g. Finally, this and all other mechanical clocks (e.g. based on oscillations of a balance wheel as in wrist watches) suffered from unpredictable changes in time-keeping accuracy with wear and tear of the mechanical parts.

Mechanical time keeping devices were useful in telling the time whenever we wanted. As a time standard, however, the rotation rate of the earth proved to be more regular than anything man-made. Despite the many advances in technology of mechanical clocks, they were still less accurate than the earth 'day'. Moreover, the success of astronomical calculations in the 19th century led scientists to believe that any irregularities in the earth's

[1] This is the familiar result from high school that $T = 2\pi\,(l/g)^{1/2}$. The fact that the period of the pendulum is independent of the mass of the bob has a lot of important physics buried in it. It comes from the principle of equivalence which states that the inertial mass (which is what you use when calculating momentum mv or acceleration F/m) is exactly equal to the gravitational mass (which determines weight). This principle was exploited by Einstein to formulate the general theory of relativity.

Time measurements became significantly more accurate only with the use of pendulum clock in the 17th century.

rotation rate could be adequately accounted for by theory. Therefore, until 1960, the unit of time 'second' was defined as the fraction 1/86400 of the 'mean solar day' as determined by astronomical theories. The earth's rotation rate was the primary time standard, while mechanical clocks were used as secondary standards whose accuracy was determined by how well they kept time with respect to earth's rotation.

As clock accuracies improved in the first half of the 20th century, especially with the development of the quartz crystal oscillator, precise measurements showed that irregularities in the rotation of the earth could not be accounted for by theory. In order to define the unit of time more precisely, in 1960 a definition given by the International Astronomical Union based on the tropical year was adopted. However, scientists were still looking for a truly universal standard based on some physical constant. They were able to do this in the late 1960s based on the predictions of quantum mechanics. As you might know, quantum mechanics was developed in the early part of the 20th century to explain the discrete energy levels and spectral lines in atoms. Planck's famous relation between the energy and frequency of a photon, $E = h\nu$, which signalled the birth of quantum mechanics, implies that atoms have a unique internal frequency corresponding to any two energy levels. Since these energy levels are characteristic of an atom anywhere in the universe, a definition based on the atom's internal frequency would be truly universal. The ability to measure such frequencies accurately was developed only about 40 years ago. Soon after, in 1967 the following definition of the unit of time was adopted: *the second is the duration of 9192631770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium – 133 atom.*

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Modern atomic clocks are built according to the above definition. The clock consists of a vacuum chamber with a caesium atomic beam, and a radio-frequency oscillator which is tuned to drive the atoms between the two hyperfine levels. There is maximum transfer of energy from the laboratory oscillator to the atoms when the atoms are in *resonance*, i.e. the oscillator frequency matches the internal frequency of the atom. A feedback circuit locks these two frequencies and ensures that the laboratory clock does not drift with respect to the atom frequency (*Box* 2). With this feedback, the best atomic clocks (used as primary standards) are so precise that they lose less than 1 second in a million years! The time standard is also universal in the sense that anybody who builds an atomic clock will get exactly the same frequency because all atoms are identical, and their behaviour under controlled experimental conditions is the same anywhere in the universe.

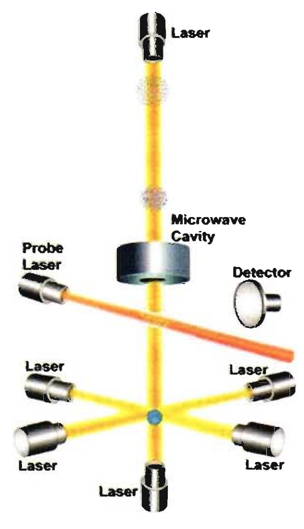
Box 2. Resonance Measurements

Measuring the frequency in an atomic clock is similar to pushing a child on a swing. The child has a natural oscillation frequency on the swing and can be thought of as the atom. The person pushing the child periodically can be thought of as the laboratory oscillator. If the two frequencies are identical, the person will give a push to the child each time the child reaches her and will keep the child swinging. On the other hand, if the two frequencies are not identical, the pushes will come at random times, sometimes slowing the child and sometimes speeding it up. The average effect will be lower and will tend to zero as the mismatch between the two frequencies increases.

In the separated oscillatory fields technique, invented by Ramsey in 1949, there is a period when the system evolves in the 'dark', unperturbed by the driving field. In the example above, it would be like giving a push to the child and then letting the child swing unperturbed for some time before giving another push. During the time between the two pushes, the frequency difference between the two oscillators builds up as a phase difference, so that after sufficient dark time the person pushing is exactly out of phase with the child and the second push brings the child to a complete halt. Even a small frequency difference can be built up to a large phase difference by increasing the dark period. Thus the frequency (or rather the frequency mismatch) can be measured more and more precisely by waiting for longer and longer times between the two pushes. This is the advantage in the latest caesium clocks – by using laser cooled atoms in a fountain arrangement the dark period is about 1 second, whereas in older atomic clocks with thermal beams the dark period was a few milliseconds.

Life in the modern high-technology world has become crucially dependent on precise time. Computers, manufacturing plants, electric power grids, satellite communication, all depend on ultra-precise timing. One example that will highlight this requirement is the global positioning system (GPS), which uses a grid of satellites to tell the precise location of a receiver anywhere on earth. Transport ships plying the vast oceans of the world now almost completely rely on the GPS system for navigation. The system works by triangulating with respect to the three nearest satellites. The distance to each satellite is determined by timing the arrival of pulses travelling at the speed of light. It takes only a few millionths of a second for the signal to reach the receiver, which gives an idea of how precise the timing has to be to get a differential reading between the three signals. Such demands of modern technology are constantly driving our need for ever more precise clocks. The caesium fountain clock shown in *Figure* 2 is one example of how the latest scientific research in laser cooling has been used to improve the accuracy of the clock by a factor of 10. Another promising technique is to use a single laser-cooled ion in a trap and define the second in terms of the energy levels of the ion. The ion trap represents an almost ideal perturbation-free environment where the ion can be held for months or years. Perhaps one day in the not so far future we will see ion trap clocks in all homes!

Figure 2. Caesium atomic clock. The figure is a schematic diagram of the caesium fountain clock at NIST, Boulder, USA. The clock has several laser beams used to cool caesium atoms to a ball at a temperature below 1 mK. The vertical lasers are then used to gently launch the atoms upwards into a microwave cavity. The atoms are interrogated once on their way up and again on their way down after they are turned around by gravity. This method of resonance detection is called the separated oscillatory fields technique and was invented by Norman Ramsey (for which he shared the Physics Nobel Prize in 1989).



Length Standards

As mentioned before, for a long time length standards were based on arbitrary measures such as the length of the arm[2] or foot. The first step in the definition of a rational measure for length was the definition of the 'metre' by the French in 1793, as a substitute for the yard. It was defined such that the distance between the equator and the north pole, as measured on the great circle through Paris, would be 10000 kilometres. This gave a convenient length scale of one metre which was very close to the old yard but now invariant. A prototype metre scale made of a platinum-iridium bar was kept in Paris. The alloy was chosen for its stability and exceptionally low thermal expansivity. Copies of this scale were sent to other nations and were periodically recalibrated by comparison with the prototype.

[2] Even now, roadside flower sellers in Madras will sell *mallipoo* by the *mozham*, defined as the length of the seller's arm from the elbow to the tip of the extended middle finger.

The limitations of the artifact metre scale in terms of invariance became apparent as more precise experiments started to be conducted in the 20th century. Again the results of quantum mechanics provided a solution. Each photon has not only a frequency (ν) but also a wavelength (λ), with the two related by the speed of light (c),

$$\nu\lambda = c.$$

Therefore if an atom is excited, it decays to the ground state by emitting photons of well-defined wavelength corresponding to the energy difference between the two levels. These photons form a unique line spectrum, or wavelength signature, of the particular atom. The wavelength of photons can be measured precisely in optical interferometers by counting fringes as a function of path length difference in the two arms. Each fringe corresponds to a path length difference of λ. Therefore, in 1960, the artifact metre scale was replaced by a definition based on the wavelength of light – 1 metre was defined as 1650763.73 wavelengths of the orange-red line in the radiation spectrum from electrically excited krypton-86 atoms. Anybody who wanted to make a standard metre scale could do it by comparing to the krypton line, thus making it universally reproducible.

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The advent of lasers has made the measurement of wavelength in optical interferometers very precise. In addition, the frequency of the laser can be measured accurately with respect to atomic clocks. In order to eliminate the fact that the definition of the metre was tied to the wavelength of a particular line from the krypton atom, the metre was redefined in 1983 using the above frequency-wavelength relation: *1 metre is the length of the path travelled by light in vacuum during a time interval of 1/299792458 of a second.* It is important to note that this definition makes the speed of light exactly equal to 299692458 m/s and demonstrates our faith in the special theory of relativity which postulates that the speed of light in vacuum is a constant. As our ability to measure the metre becomes more accurate, it is the definition of the metre that will change in order to keep the numerical value of the speed of light a constant. In this sense, we have actually dispensed with an independent standard for length and made it a derived standard based on the standard of time and a fundamental constant of nature c.

In 1983 a metre was redifined as the length of the path travelled by light in vacuum during a time interval of 1/299792458 of a second.

Using iodine stabilized HeNe lasers (see *Figure* 3), the wavelength of light and thus the definition of the metre is now reproducible to about 2.5 parts in 10^{11}. In other words, if we were to build two metre scales based on this definition, their difference would be about one million times smaller than the thickness of a human hair!

Mass Standards

In olden societies, mass standards were based on artifacts such as the weight of shells or of kernels of grain.

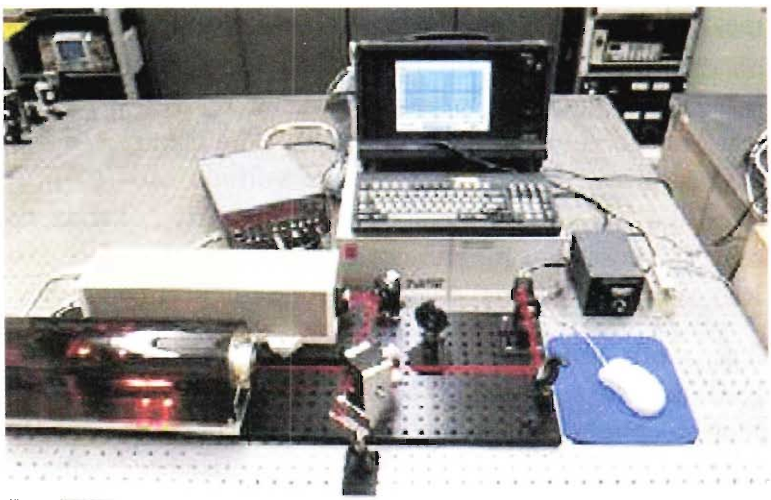

Figure 3. Length calibration. The photo shows an iodine stabilized HeNe laser (in the foreground), which is used as a length standard to calibrate the wavelength of a second laser (behind the iodine stabilized laser). The calibrated second laser is then used for ultra-high precision measurements in both laboratory and industrial settings. The laser in the photograph was built by Jack Stone of NIST.

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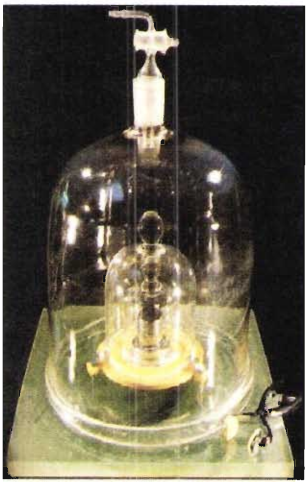
The first scientific definition of mass adopted in the 18th century was the 'gram', defined as the mass of 1 cubic centimeter of pure water at 4°C. This definition made the density of water exactly 1 g/cc. The definition survived till almost the end of the 19th century. It was replaced in 1889 when the 1st General Conference on Weights and Measures sanctioned an international prototype kilogram to be made of a cylinder of platinum-iridium alloy and kept at the International Bureau of Weights and Measures in France (see *Figure* 4). It was declared that henceforth the prototype would be the unit of mass. Among the base units, mass is the only one that is still based on an artifact and not on some fundamental property of nature. Environmental contamination and material loss from surface cleaning are causing the true mass of the kilogram to vary by about 5 parts in 10^8 per century relative to copies of the prototype in other nations. There are many physical constants which depend on mass, and the drift of the mass standard means that these constants have to be periodically revised to maintain consistency within the SI system.

Figure 4. Prototype mass standard. The picture shows the platinum-iridium international prototype kilogram, as kept at the International Bureau of Weights and Measures in Paris, under conditions specified by the 1st General Conference on Weights and Measures in 1889.



There are several proposals to replace the mass standard with a universal one based on physical constants. There are two major approaches taken in this effort – one is based on electrical measurements and the other is based on counting atoms. In the electrical measurement approach, an electrical force is balanced against the gravitational force on a kilogram mass. The electrical force is determined by the current and voltage used to produce the force. As we will see later, electrical standards are now based on fundamental constants, therefore the kilogram will also be related to fundamental constants.

The atom counting approach is a promising proposal that uses the tremendous advances made in silicon processing technology in recent decades. It is now possible to make large single crystals of silicon with very high purity and a defect rate that is less than one part in 10^{10}, i.e. atoms in the crystal are stacked perfectly and less than one atom in 10 billion is out of place! Such single crystals also cleave along certain symmetry planes with atomic precision, i.e. the crystal facet after a cut is atomically flat. Laser interferometry can be used to measure the distance between the outer facets of the crystal very precisely. This yields the precise volume of the crystal. Similarly, X-ray diffraction can be used to measure the spacing between successive atoms (lattice spacing) very precisely. The volume and the lattice spacing effectively tell us how many atoms there are in the crystal. From the definition of a mole we know that N_A silicon atoms will have a weight of $M_{Si} \times 10^{-3}$ kilograms, where N_A is Avogadro's constant and M_{Si} is the atomic mass of silicon. Therefore, a knowledge of the physical constants N_A and M_{Si}, combined with length measurements for the size of the crystal, will give the mass of the sample in kilograms. The present limitation in using a silicon mass standard is the precise knowledge of N_A. However, there are several experiments currently being performed that might yield a more precise and useful value for this constant. When this happens, the kilogram would be redefined as being the mass of a specific number of silicon atoms and we would have eliminated the only remaining artifact standard.

Modern silicon technology can be used to make such perfect single crystals of Si that less than one atom in 10 billion is out of place.

Electrical Units

Before we conclude, we will discuss the use of fundamental constants in defining electrical standards. Electrical units can all be related to the base units of mass, length and time through physical laws. For example, Coulomb's law for the force between two charges q_1 and q_2 is expressed as

$$F = K\frac{q_1 q_2}{r^2}.$$

The proportionality constant K appearing in the above equation can be interpreted in two ways. From a physicist's point of view, it is just a matter of definition and can be set to 1 without any change in the underlying physics. In such a case, the units for measuring charges are so defined that q^2/r^2 has the dimensions of force. Thus charge becomes a derived unit, which can be related to the dimensions of mass, length and time through the above equation. From a practical point of view (which is followed in the SI system of units), it is useful to assign an independent unit for charge[3] (coulomb in the SI system). The constant K then serves to match the dimensions on both sides of the equation. Thus in the SI system $K = 1/4\pi\epsilon_0$, with ϵ_0 having units of farad/metre. It should be emphasized that both points of view are valid, however the latter introduces concepts such as permittivity of vacuum which needlessly complicates our understanding of physics.

[3] In SI units, it is actually the ampere which is the base unit. It is defined as the constant current that has to flow along two infinite parallel conductors placed 1 metre apart so as to produce a force of 2×10^{-7} N/m. In this system, 1 coulomb is 1 ampere-second.

Whatever the point of view, the units have to be consistent with Coulomb's law. Therefore, two unit charges placed unit distance apart in vacuum should experience a force of K units. This is how electrical standards have to be finally related to the mechanical standards in a consistent manner. While it may not be practical to measure forces on unit charges this way, there are other consequences of the electromagnetic laws which make a practical comparison of electrical and mechanical units possible. For example, it is possible to measure electrical forces in current carrying conductors by balancing them against mechanical forces. This would be a realization of the ampere.

The Josephson effect relates the frequency of an ac current generated when a dc voltage is applied across a tunnelling junction between two superconductors.

These traditional methods of defining electrical standards have showed a lot of variation over time. However, recently it has been possible to base the definitions of electrical quantities using invariant fundamental constants. Two effects are used for their definition: the Josephson effect, and the quantum Hall effect. The Josephson effect relates the frequency of an ac current generated when a dc voltage is applied across a tunnelling junction between two superconductors. The frequency of the current is given by

$$f = \frac{2e}{h}V,$$

where e is the charge on the electron. In SI units, a dc voltage of 1 μV produces a current with a frequency of 483.6 MHz. The dc voltage can therefore be related to the time or frequency standard through the fundamental constant $h/2e$. The quantum Hall effect is a phenomenon discovered by von Klitzing in 1980. He showed that at low temperatures and high magnetic fields, the Hall resistance in certain semiconductor samples shows quantized steps (see *Figure* 5). The fundamental unit of resistance is h/e^2 (about 25.7 kΩ in SI units) and the steps occur at values of this constant divided by an integer i. Since 1990, the SI standard of ohm is defined through the steps in the Hall resistance of a semiconductor sample. Given the robust nature of the steps, it is easy to reproduce the resistance and its value is determined only by physical constants. The standard volt and ohm in the SI system have thus been successfully

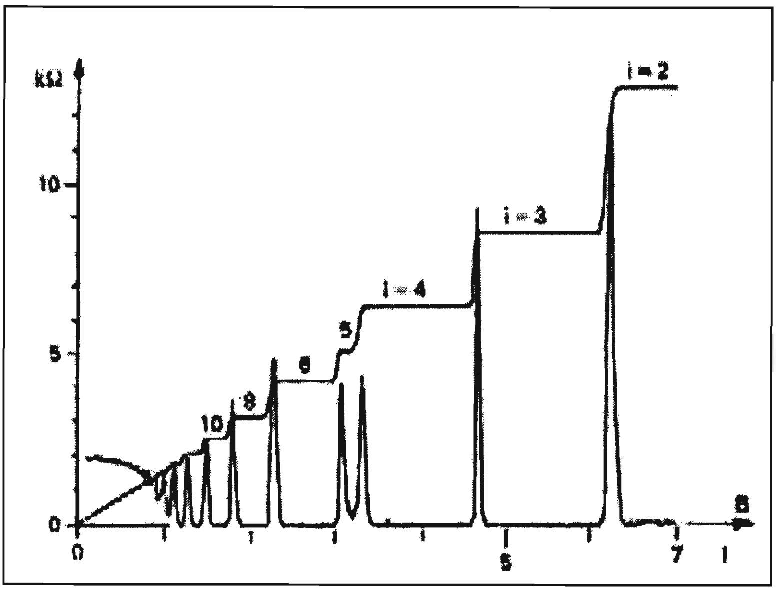


Figure 5. Quantum Hall effect. The plot shows the steps in the Hall resistance of a semiconductor sample as a function of the magnetic field. The steps occur at values given by the fundamental constant h/e^2 divided by an integer i. The figure shows the steps for i=2,3,4,5,6,8 and 10. The effect is called the quantum Hall effect and was discovered by von Klitzing for which he won the Physics Nobel Prize in 1985. Since 1990, the effect has been used for a new international standard for resistance called 1 klitzing, defined as the Hall resistance at the fourth step ($h/4e^2$). The lower peaked curve represents the Ohmic resistance, which disappears at each step.

Box 3. Fun with Dimensions

It is somewhat instructive to play with dimensions of fundamental constants to see how they result in phenomena that can be used for defining standards. For electrical phenomena at the quantum level, there are two constants – the charge on an electron or proton e, and Planck's constant h. In the SI system, the units of e are coulombs and that of h are joules/hertz. It can then be verified that h/e has the dimensions of volts/hertz which is the quantum-mechanical voltage-frequency conversion factor. The actual factor in the Josephson effect is $h/2e$, but the factor of 2 can be understood when we remember that the basic charge carriers in a superconductor are paired electrons which thus carry charge of $2e$. Similarly h/e^2 has dimensions of ohms, and is the basic unit of quantum resistance in a semiconductor sample.

Continuing with this theme, we expect a deeper understanding of inertia when we develop a satisfactory theory of relativistic quantum gravity. The fundamental constants that are expected to be important in such a theory are c, corresponding to the relativistic part of the above theory, h, corresponding to the quantum part, and Newton's constant G, corresponding to the gravity part. These constants have values 3×10^8 m/s, 6.6×10^{-34} J/Hz, and 6.7×10^{-11} Nm^2/kg^2, respectively. The three constants can be combined in various ways to get other constants which have dimensions of mass, length, and time. Together the new constants set the scale at which we expect quantum gravity effects to become significant. This is called the Planck scale. Thus the Planck length $(hG/c^3)^{1/2}$ is 4×10^{-35} m, the Planck time $(hG/c^5)^{1/2}$ is 1.3×10^{-43} s, and the Planck mass $(hc/G)^{1/2}$ is 5.4×10^{-8} kg. It looks as though only the Planck mass scale is currently accessible to human technology, and perhaps we will not understand quantum gravity until we can access the Planck length and time scales.

tied to fundamental constants of nature. The definition of current (ampere) follows from Ohm's law $I = V/R$.

Conclusions

We have thus seen a trend where fundamental constants play an increasingly important role in eliminating artifact standards and in deriving some units from others.

We have thus seen a trend where fundamental constants play an increasingly important role in eliminating artifact standards and in deriving some units from others. Our faith in physical laws makes us believe that these constants are truly constant, and do not vary with time. Ultimately, we would like to find enough fundamental constants that we are really left with only one defined standard and all others are derived from it. Certainly what we have learnt in high school that the study of mechanics requires three independent units (or dimensions) of mass, length and time is not completely correct.

Using the special theory of relativity, we have reduced this to two, mass and time. All indications are that when we understand the force of gravity from a quantum mechanical perspective, mass (or inertia) and spacetime will be linked in a fundamental way (see *Box* 3). When this happens, the unit of mass will most likely be fundamentally related to the unit of time. We will be left with just one arbitrary definition for 'second' which sets the scale for expressing all the laws of physics. Someday, if we were to meet an intelligent alien civilization and would like to compare their scientific knowledge with ours, we would only need to translate their time standard to ours. Will this ever happen? 'Time' alone will tell!

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Acknowledgements

The author gratefully acknowledges the following for granting permission to reproduce the figures: For further reading, please visit the respective websites.

Figure 1. Nikolaus von Bomhard
http://www.bomhard.de/_englisch

Figure 2. National Institute of Standards and Technology (NIST), USA
http://www.boulder.nist.gov/timefreq/cesium/fountain.htm

Figure 3. NIST, USA

Figure 4. Bureau International des Poids et Mesures, France
http://www.bipm.org/enus

Figure 5. Nobel Foundation, Sweden
http://www.nobel.se/physics/laureates/1998

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