OUR UNITS OF MEASUREMENT*

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Prof. R.K. Pathria is an eminent theoretical physicist, known for his work on superfluidity in liquid helium and phase transitions. The book "Statistical Mechanics" authored by him still continues to be a popular title among undergraduates and is an international bestseller on this subject. Prof. Pathria is currently a professor emeritus at the university of Waterloo.

In this article, Prof. R.K. Pathria provides a comprehensive history about the use of different units of measurement. Through this series of four articles, the author attempts to narrate the exciting and thrilling story of the adoption of different units of measurements, dominated by the flavour of an ever-increasing degree of scientific precision which forms the central theme of the series. Each article covers different units—length, time, weight, luminosity, electricity and magnetism. Part I and II cover the most basic measurements a student of physics has to deal with, which are the ones related to the three fundamental entities of Nature—space, time and matter. These measurements constitute the elementary processes of determining the length of a straight line joining two given points of space, the time interval elapsed between two given instants of time, and the mass of a given piece of matter. Part I focuses on length while part II focuses on time and mass. In part III, the author reviews the sequence of developments that finally led to the adoption of the fundamental units employed with respect to heat and light; thermometry and calorimetry are discussed in case of heat and for light the fundamental units employed in photometry. In the concluding article, part IV, the units of measurement employed in the domain of electricity and magnetism are discussed. The author limits the discussion to those aspects which he considers vital to have a holistic perspective.

Keywords: Unit, Measurement, Length, Time, Weight, Light, Heat, Electricity, Magnetism

PART I

In our study of science, we are primarily concerned with the art of creating order out of chaos which is invariably met with during the process of observation of the various phenomena of nature; accordingly, our most persistent intellectual efforts are directed towards the discovery of a certain well-knit pattern, design, system or structure of ideas and thoughts, in terms of which the elements of our experience with the physical world can be interpreted. Thus, as was nicely put by the famous British mathematician and philosopher A.N. Whitehead (1861–1947), 'to see what is general in what is particular and what is permanent in what is transitory is the major aim of all scientific endeavour'.

Now, the first and the foremost step necessary for the attainment of this cherished objective consists in making measurements on things. In fact, it is only through a rational analysis of the results of these measurements that we obtain a glimpse of the orderliness that governs the phenomenon under study. Quite naturally, the scientist strives to make his process of measurement more and more systematic and refined and his mode of analysis more and more thorough and rigorous. It so happens that in both these respects, the science of physics is by far the most advanced of all sciences. To this extent,

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therefore, it may be looked upon as the basic science; indeed, a number of scientific disciplines which have emerged from time to time originally started as merely different branches of the mainstream of physics.

In physics, again we can discern certain domains of activity which are intuitively more basic than others, for instance, the preliminary, and in some sense fundamental, study of the elements of space, time and matter. The most basic measurements, the student of physics has to deal with, are the ones related to these three entities of nature. These measurements, in principle, constitute the elementary processes of determining (i) the *length* of a straight line joining two given points of space, (ii) the *time interval* elapsed between two given instants of time, and (iii) the mass of a given piece of matter. In order to state these measures numerically, we ought to define the respective *units of measurement,* in terms of which the results of an actual process of measurement could be expressed. And, in order that the results so stated be both unambiguous and free from personal factors, the units employed must be such as; are quite faithfully reproducible and quite universal in character. It is indeed a matter of genuine satisfaction that, through centuries of experimentation and contemplation, these requirements have now been met to a really remarkable degree of accuracy. To narrate the exciting and thrilling story of these attainments, dominated by the flavour of an ever-increasing degree of scientific precision, is the central theme of the present series of articles.

In the first two instalments of the series, viz., I and II, our discussion will largely confine itself to the aforementioned three *fundamental* units. Noting that certain suitable combinations of these units enable one to define any of the so-called derived units of mechanics—the subject dealing with the motion, in space and time, of matter the discussion of these two parts may be regarded as practically complete insofar as the mechanical quantities are concerned. The consideration of the non-mechanical quantities, however, necessitates the introduction of a few more fundamental units of measurement; these will form the subject-matter of the remaining part of the series.

Emergence of the Unit of Length

(Historical Background)

About five thousand years ago, in the great river valleys of Egypt and Mesopotamia (the latter now approximating to the state of Iraq), the royal surveyors were already mapping their masters' fields, while the royal architects were planning the Temples, Palaces and Tombs. These activities led to the development of practical geometry into a serviceable body of rules, characterised by a secure tradition and a great uniformity of practice. Over a score of centuries the master builders of Egypt were employing a unit of length, namely the *cubit*—defined by the distance from the elbow to the tip of the middle finger—which, in actual practice, did not vary by much more than 1 part in 200 from the mean. Later on, with a view to regulating all measurements on the rise and fall of the waters of the Nile, a standard cubit was kept in the capital in priestly custody; besides this, there was marked by official decree, the unit *schoenus,* an itinerary standard of 12,000 cubits, on the road from Memphis to Faium. This bespeaks very admirably the great attention these people paid to the preservation of a common linear standard.

Nearly a thousand miles away from the site of the Egyptian civilisation, i.e. in Mesopotamia, during much the same period, essentially the same standard of length—the cubit was maintained, with almost equal exactitude. Interestingly enough, the mention of this very unit of length is made in the *slokas* of some of the early Indian writings as well. Here, it appears by the name *hasta,* implying precisely the same definition as adopted in the other two civilisations. This was possibily the most handy of all the units one could imagine.

With the decline of these practical minded civilisations, there arose, in the first millennium B.C., the famous civilisation of the Greeks. One of the many influences this civilisation had on the course of scientific development was the replacement of the hitherto practical geometry by the new abstract geometry, which originated in the genius of the first individual scientist the world has ever known, namely Thales of Miletus (c. 624–547 B.C.), received successive additions and refinements from men like Pythagoras (c. 572–497 B.C.) and Eudoxus (c. 408–355 B.C.), and got brilliantly systematised by the great teacher Euclid (c. 330–275 B.C.). The resulting concept of the abstract space, namely the Euclidean space, to which the actual space of our physical experience so closely approximates, was thereby accepted as providing a highly workable spatial frame-work of physics.

Based as it was on a set of highly plausible definitions, axioms and postulates, the Euclidean geometry, by virtue of its rich treasure of theorems and corollaries, put the subject of length measurement on a sound theoretical basis. One could now picture quite unambiguously as to how to estimate, at least in principle, any given length in terms of an arbitrary unit of length (adopted for the purpose of measurement) and its sub-multiples, to within any specified residual uncertainty. The numerical result could, in general, be expressed in any agreed system of arithmetical fractions. It may be of interest to mention that the system of fractions that was in vogue in the times of Euclid and practically remained so, in Europe, until about the early parts of the seventeenth century was the one based on sexagesimal fractions (with the base 60, which almost certainly was of a Sumerian-Babylonian origin, dating back to about 1700 B.C.). This system of arithmetical expression, along with the others such as the Roman system, got universally replaced by the illustrious decimal system (with Arabic numerals) which, in all essentials, was developed by the Hindu mathematicians of the Vedic period (1500–750 B.C.), was carried over to the West through the intermediary of the Arabs (in the beginnings of the second millennium A.D.) and introduced into the European learning through the advocacy of the Dutch mathematician Simon Stevinus (1548–1620), and the English mathematician Henry Briggs (1556–1630). At present, this is practically the only system of notation one has to speak about.

Having developed the logical methods of comparing lengths and expressing numbers in a suitable arithmetical notation, the major problem of practice consisted in selecting an appropriate unit and preserving it in the form of a material standard. Reference has already been made to the cubit and to the official preservation of the corresponding standard in charge of the priests. By and by, a number of other units, either derived from the cubit or defined independently, also came into practical use. With the advent of the Scientific

Renaissance in Europe, in about the fifteenth century, the regions of scientific activity started spreading over a larger and larger number of countries over the continent; along with that, there came into adoption a still larger variety of units of length measurement. These units, due primarily to the lack of effective communication and also due to the lack of realisation of the desirability of having a certain uniformity of units, varied from state to state and even from town to town. Any detailed description of this bewildering variety of units, both of weights and measures, would make our account here annoyingly unwieldy. Suffice it to say that in the eighteenth century France, with the largest population in Europe and engaged mainly in agriculture and domestic industry, the situation was chaotic. And the same was true of almost any other country of Europe, but for England where a strong central government and mercantile development had imposed and maintained a unified system of weights and measures at least from the time of Edward III (1312–1377). The sub-divisions of the British standards, however, have been and still are, at variance with the decimal system; accordingly, these standards have been found rather unfit for universal adoption. We shall, therefore, skip over the history of establishment of these standards and pass on to the consideration of their French counterparts.

Admittance of the Metric System

The first effective step towards the formulation and establishment of a national system of weights and measures in *decimal notation* was taken in France, within a year of the outbreak of the revolution in 1789. In accordance with the aims of the revolution, and also in line with the scientific spirit of universality, it was intended to base the fundamental units of measurement on certain natural standards common to all men.

Among the academicians of the land, suggestions had already been made from time to time about basing a new and standard system of measurements on some suitable physical constants. In regard to the unit of length measurement, for instance, the astronomer Jean Picard (1620–1682) suggested as early as 1671, 'the length of a pendulum beating seconds, i.e. having a time period of two seconds' as the requisite standard, although he seems to have rightly suspected that this length would vary with latitude. In 1748, the mathematician Charles-Marie de la Condamine (1701–1774) recommended, 'the length of a seconds-pendulum *at the equator*' as the desired standard, On 8 May 1790, the National Assembly decreed that the Academy explore the possibility of adopting this standard as the national or even the universal, unit of length measurement. In this decree, however, there was no mention of the decimal notation.

In the Academy, however, matters went differently. The academicians decided to investigate side by side a different but all-the-more fascinating, suggestion, first put forward by the astronomer Jacques Cassini (1677–1756) in 1720, namely that a suitable fraction of the meridian between the terrestrial pole and the equator be taken as the required standard. The question of an accurate practical measurement of the meridian was indeed very difficult; but the academicians had already taken keen interest in this problem from the point of view of 'the figure of the earth', that is, whether it was flattened or elongated towards the poles. They regarded this problem almost their own and hence preferred to make use of a part of the funds made available by the Assembly in the investigation of this leading scientific problem. As Biot (1774–1862), wrote a few years later, 'science also has its politics'.

It was the Commission appointed for going into the relative merits of these two rival suggestions that recommended on 27 October 1790, the use of decimal notation in the new system. Later, on 19 March 1791, they recommended that the measurement of an arc of the meridian would be preferable to the use of the seconds-pendulum for the main reason that the latter definition involved the unit of time and hence undermined the necessity of defining the fundamental units of measurement independently of one another. From the measurement of an arc of the meridian, on the other hand, if one were to derive the length of a quarter of the earth's meridian (in terms of any arbitrary unit of length), *one ten-millionth part of which* —later denominated as the *metre* (whence the system itself derives the name the *metric* system) *would be taken as the unit of length measurement*. The National Assembly adopted these recommendations on 26 March 1791.

In 1792, active work commenced on this project, namely the measurement of the length of the meridianal arc between Dunkirk (France) and Barcelona (Spain). The pace of progress, however, was quite slow. Impatience with the slow progress of the work and urgency of the need of a standard led the National Convention (which had by then replaced the Legislative Assembly) to adopt, in September 1793, a *provisional* metre, based on the earlier measurements of the Paris meridian by the astronomer Nicolas-Louis de Lacaille (1713–1762). Material standards were to be prepared under the supervision of the Academy and sent to all local administrations throughout France. Corresponding changes were to be incorporated in the school textbooks of arithmetic and the use of the new unit was to become obligatory with effect from 1 July 1794.

Political events, however, took a new turn. On 8 August 1793, the Academy of Sciences and all other learned societies were suppressed by the order of the Convention. A number of leading academicians were dismissed on flimsy grounds and consequently, work on all scientific projects was seriously hampered. It could restart effectively only when the *Institute National* was established as successor to the suppressed Academy. The geodetic work, begun in 1792, got completed only towards the end of 1798. This enabled the replacement of the provisional metre of 1793, by a more dependable one, the latter being approximately 0.3 mm shorter, The corresponding platinum end-standard, of cross-section 25.3 × 4 mm was constructed and adjusted by Janetti so that its end-to-end length at 0°C was equal, as near as possible, to the unit deriving from the measured terrestrial meridian and on 22 June 1799, it was deposited, with full diplomatic and legislative ceremony, in the National Archives. The new standard (named *Métre des Archives),* along with its decimal sub-multiples, was approved as legal on 10 December 1799, becoming compulsory in 1801. In practice, however, the adoption was rather slow and as late as 1837, the French Government had to pass a law forbidding, under severe penalties, the use of the old units as from the New Year's day of 1840.

By 1872, seven other European states and a good part of South America had adopted the new system. Great Britain legalised its *optional* use in 1864 and is, at present, considering the desirability of its full-fledged adoption. We, in India, have also recently admitted it into use by the rule of law.

Establishment of the International Prototype Metre

Shortly, after the adoption of the Métre des Archives, the investigators who had worked on the geodetic measurement prepared a fresh and detailed account of their findings and arrived at the conclusion that the metre adopted by the special commission was rather too short. Instead of expressing their conclusion in numerical terms, it appears more appropriate to indicate, in relation to the *modern* value of the ten-millionth part of a terrestrial quadrant, that the adopted metre was about 0.2 mm (i.e. 1 part in 5000) shorter than the intended one, the carlier provisional one thus being about 0.1 mm in excess of the intention. Thus, the fundamental unit of length was ultimately arbitrary.

A closer reflection at the problem, however, readily reveals the hollowness of the doctrine that the fundamental units *must* be derived from certain universal sources. It is obvious that, irrespective of the mode of definition and the source of derivation, any specified unit is, in the last analysis, bound to be arbitrary. In fact, the only serious consideration that need be given to the problem of the units is the one in regard to the possibility of their *faithful and unambiguous reproduction* (of course, under a suitably laid down set of physical conditions). Accordingly, the fiction of a certain pre-assigned relationship between the fundamental standard of length and the Earth-quadrant has got to be quietly forgotten.

In the sixties of the last century, as the popularity of the decimal metric system began spreading from state to state, suggestions started pouring in that *new* metric standards (of length and mass) be prepared and their official copies constructed and distributed to the various organisations. The French Government thereupon took necessary steps in this direction. As a result, there came into creation, in 1875, the *Bureau International des Poids et Measures (*BIPM)-the International Bureau of Weights and Measures-comprising a central laboratory and office located at Sévres, near Paris. The work of the BIPM (which now includes the fundamental metrology of temperature, photometry, electricity and the ionising radiations) is managed by an International Committee of Weights and Measures, meeting every two years, which is elected by and under the authority of, the General Conference of Weights and Measures, meeting every six years. The membership of the General Conference now extends over about forty states.

The International Committee resolved that, in order to maintain the continuity of use, the new standard of length be defined as equal to the Métre des Archives and, from the point of view of satisfactory preservation, it be reconstructed from an alloy of 90 per cent platinum and 10 per cent iridium, which, for its metrological qualities, had already been studied by the physicist Fizeau (1819–1896), and the chemist Deville (1818–1881). Instead of making the new standard of the end-type, it was considered preferable to make it line-type, by casting it in the form of a bar, of a special cross-section shown in Fig. 1 (so designed by the engineer-metallurgist Tresca (1814–1885), as to give it maximum rigidity for a given quantity of the precious alloy used and also to ensure that the plane surface exposed in the upper channel of the bar was a part of the neutral surface when the bar sagged on its supports), the bar bearing on its exposed neutral plane two parallel defining lines, separated at, 0°C, by the distance equal to the unit metre length as represented by the Métre des Archives. The neutral plane of the bar is clearly the most suitable of all planes because the distance between the lines engraved thereon is least influenced by the manner of supporting the bar. Nevertheless, it was also specified that the bar be symmetrically supported on two rollers at right angles to its length and 0.571 metre apart (for a bar of total length about 101.6 cm); with this specification, the actual distance between the defining lines would be least sensitive to the separation between the rollers which is again important from the reproducibility point of view.

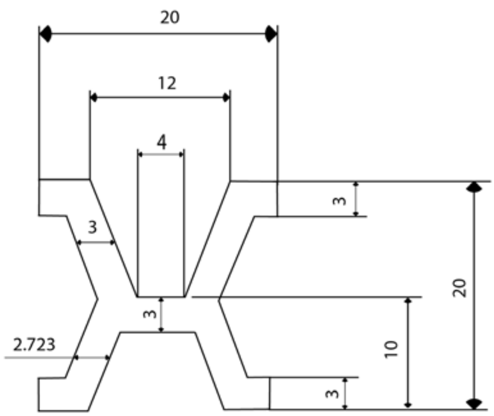

Fig. 1. Cross-section designed by Tresca for the former International Prototype Metre and the national copies (dimensions in mm) (after Barrel)

Because of the difficulties in the metallurgy of the specified alloy, actual work of construction of the new standards could not make a satisfactory headway until the late eighties. The specimen finally accepted was the one now known as the Johnson-Matthey alloy, containing 89.75–90.25 per cent of platinum and 9.75–10.25 per cent of iridium, with small tolerances for impurities such as ruthenium, rhodium, palladium, copper, silver, gold and other elements. A number of metre copies were made of this alloy and were ready for distribution when the first General Conference met in Paris in September 1889. One of these copies was denominated as the *International Prototype Metre,* superseding the Métre des Archives, the length of the former having been declared as equal to that of the latter (within the limits of experimental error, namely about 1 μm=10^{-6}m) and was kept at the headquarters of the BIPM at Sévres. Official copies, with certified lengths, given in terms of the metre represented on the Prototype, were distributed among the member-states.

The refined definition of the metre, adopted later by the 7th General Conference in 1927, reads as follows:

> The unit of length is the Metre, defined by the distance, at 0°C, between the axes of two transverse lines engraved on the platinum-iridium bar kept at the International Bureau of Weights and Measures and declared to be the Prototype of the Metre by the First General Conference of Weights and Measures, this bar being kept at the normal atmospheric pressure and supported by two rollers of mean diameter one centimetre placed symmetrically in the same horizontal plane and a distance of 571 mm apart.

We notice that the definition of the metre requires the bar to be at the naturally fixed temperature of melting ice. In practice, however, it is not always convenient to make comparisons at 0°C, even of the primary standards in the laboratory; rather, for everyday use lengths must be standardised at normal working temperatures. It thus follows that a knowledge of the coefficients of thermal expansion of these bars is required; accordingly, much effort has been put into determining the thermal dilatations of metals used for constructing the length standards, and particularly of the platinum-iridium alloy.

Next, it is interesting and important to have an idea of the degree of precision attained in the comparison of the various metre bars and the degree of constancy with which the fundamental unit has been maintained since its inception in 1889. The difference between two metre-standards provided with modern defining lines can be determined with an uncertainty not exceeding 0.1/μm. Such a precision cannot possibly be guaranteed for the whole family of metre bars as ruled in 1889, because of the general lower quality of the lines engraved at that time in comparison with the modern rulings; indeed, many of the original copies have, during the past few years, been re-ruled. Nevertheless, it can be safely said that the International Prototype and its copies have preserved the unit metre distance with a precision of about 0.2 μm i.e. 2 parts in 10^7.

The Optical Metre

Although the International Prototype Metre and its official copies did preserve the fundamental unit of length quite adequately, the problem of reproducing the metre quickly and correctly still remained largely unsolved. It appeared, no doubt, highly desirable to evolve an alternative definition, which could enable one to realise the metre in any reasonably equipped scientific laboratory *without recourse to the reference bars preserved at a limited number of stations.* One therefore notes with a sense of innate satisfaction that, as a result of the high precision work carried out in the field of atomic spectroscopy during the present century, the metre has finally been defined through an atomic standard which gives it an accuracy of about 1 part in 10s in the matter of reproducibility. Incidentally, then, one of the major objects of the French reform, namely the use of an invariable universal natural standard for a physical unit, has at last been achieved; the arbitrariness of the definition is, of course, bound to remain.

This part of the story again starts with a Frenchman, the physicist Babinet (1794–1872), who for the first time drew attention, in 1829, towards the concept of employing the wavelength of some suitable light-wave as a standard of length. In 1889, the American physicist Michelson (1852–1931), and his famous collaborator, the chemist Morley (1838–1923), published a paper 'On the feasibility of establishing a light-wave as the ultimate standard of length', in which they described as to how one could employ the now well-known Michelson interferometer in order to determine the number of wavelengths contained in a metre.

The practical work in this direction started at the BIPM during 1892–93, when the first direct measurement of the metre in terms of the wavelength of the red light of cadmium was made by Michelson and Benoit. In 1905–06, Benoit, Fabry and Perot improved upon the accuracy of this measurement and announced that this wavelength is, within the limits of experimental error, 6438.4696 × 10^{-10} m in standard air; the reader may keep in mind that the modern specification of standard air for spectroscopy and metrology is: dry air, at 15°C, under a pressure of

1013250 dynes/cm² and containing 0.03 per cent by volume of carbon dioxide. In 1907, the International Solar Union (now the International Astronomical Union) adopted the wavelength of cadmium red line as the reference basis for all spectroscopic measurements of wavelengths and defined its value in terms of the International angstrom (A) as *exactly* 6438.4696 A, the unit A thus being provisionally equal to 10^{-10} m but subject to minor possible changes consequent upon any later improvement in the experimental value of the wavelength in question. The 7th General Conference, meeting in 1927, although rejecting a proposal to adopt the cadmium standard as the ultimate reference for the metre, gave formal sanction to determinations of length being based on the value of $\lambda_R = 6438.4696 \times 10^{-10}$ m as an *alternative* to the use of the material standards. Incidentally, this implied that from now onward the angstrom unit would, by definition, be exactly equal to 10^{-10} m.

In pursuance of the foregoing sanction, a number of physical laboratories all over the world carried out fresh determinations of the number of wavelengths, in standard air, of cadmium red line contained in the metre. The weighted mean value, derived by Barrell in 1948 from nine determinations made by various investigators during the period 1892–1940, is 1553164.12, the corresponding value of λ_R being the same as adopted above, with a standard error of about 6 parts in 10^8. In a recent re-evaluation of the data, Hart and Baird (1961), derived a value of $6440.2490 \times 10^{-10}$ m *in vacuo,* corresponding to the value $6438.4695 \times 10^{-10}$ m in standard air of refractive index 1.000276381. This revision, fortunately, has not created any new difficulty of practice.

Now the question arises, as to what it was that still came in the way of defining the metre *exclusively* in terms of a wavelength standard, thus superseding the material standard altogether. The answer is that, no known optical radiation, emitted from a natural element such as cadmium, appeared to possess a significantly higher reproducibility than the best material standards. Lately, however, this did become possible, due mainly to the introduction and development of improved sources of monochromatic light, employing, instead of the natural elements, pure isotopes (and those too of even atomic charge and mass and, hence, of zero nuclear spin). This replacement results in much finer lines of emission, enabling an improvement *by an order of magnitude* in the degree of reproducibility.

The three rival claimants for the unique honour in sight, as admitted by the 9th General Conference in 1948, were the red line of the cadmium isotope ${}_{48}Cd^{114}$, the green line of the mercury isotope ${}_{80}Hg^{198}$ and the orange line of the krypton isotope ${}_{36}Kr^{86}$. A comparative study of these three lines, carried out quite intensively and extensively during the period 1954–57, clearly indicated that the krypton line among these presents the most dependable basis for an optical definition of the metre.

Basing its deliberations on the highly concordant results coming from five leading laboratories of the world, the 11th General Conference, on the 14th of October 1960, adopted the following resolution:

1. The metre is equal in length to 1650763.73 wavelengths *in vacuo* of the radiation corresponding to the

transition between the $2p_{10}$ and the $5d_5$, levels of the Kr^{86} atom.

2. The definition of the metre in force since 1889, based as it was on the International Prototype Metre made of platinum-iridium, stands repealed.
3. The International Prototype of the metre, adopted by the 1st General Conference of Weights and Measures of 1889, would remain preserved at the International Bureau of Weights and Measures under the same conditions as were laid down for it in 1889.

The source of the standard radiation, recommended in 1960, by the International Committee, is the Engelhard lamp, operated according to the following instructions:

In conformity with the paragraph 1 of the (foregoing) resolution, adopted by the 11th General Conference of Weights and Measures (October, 1960), the International Committee of Weights and Measures recommends that the Kr^{86} radiation adopted as the fundamental standard of length should be realised by means of a hot cathode discharge lamp containing krypton 86 of purity not less than 99 per cent, in sufficient quantity to ensure the presence of solid krypton at the temperature of 64°K, this lamp being provided with a capillary having the following characteristics: internal diameter 2 to 4 millimetres, thickness of the walls about 1 millimetre.

It is estimated that the wavelength of the radiation emitted by the positive column (of this lamp) would be uniform to within 1 part in 10^8 of the wavelength corresponding to the transition between the unperturbed levels, when the following conditions are satisfied:

'1. The capillary is seen through from such an end that the bright rays coming from the side of the cathode towards the anode are made use of.

2. The lower part of the lamp, including the capillary, is immersed in a cold bath maintained at the temperature of the triple point of nitrogen to within a degree.

3. The current density in the capillary is 0.3±0.1 ampere per square centimetre.'

Shortly afterwards, in 1961, Hart and Baird reported measurements, in terms of the new definition, made in the laboratories of the National Research Council, Ottawa (Canada), on four 1-metre line standards whose relationships with the former Prototype Metre were already well known. They found that the number of the standard wavelengths contained in the original metre averaged at 1650764.08, so that the new (optical) metre was shorter than the original one by about one-third of a wavelength; in more familiar terms, one could say that the new metre minus the old metre is equal to (−0.20±0.04) μm.

It is important to note that the length difference between the new and the old standards, if at all real, does not present any specific difficulties of continuity because it happens to be of the same order of magnitude as the uncertainty appearing in the preservation of the metre on a material standard and in the intercomparison of the various copies thereof. On the other hand, the new metre, unlike the old one, can be reproduced, if the stated physical conditions are guaranteed, with an accuracy of about 1 part in 10^8.

PART II

In the first part (Pathria, 1964) an attempt was made to review the sequence of steps that finally led to the adoption of the so-called optical metre as the fundamental unit of length measurement. In the present article it is proposed to discuss the corresponding situation in regard to the fundamental units of mass and time. From a strictly physical point of view, we should first consider the unit of time and only then the unit of mass. The sole reason for the reverse order chosen here is that it will provide a decidedly better continuity of narration from the first article to the present one.

The Unit of Mass

Before the time of Galileo (1564–1642), and Newton (1642–1727), there were no standards of 'mass' as such. Of course, there were plenty of standard 'weights' even two thousand years previously. From the very early times the beam balance, in a primitive form, was being employed for the comparison of weights and for many centuries it was intuitively, though not explicitly, assumed that by this procedure one indeed compared the intrinsic quantities of the materials involved. The modern man does indeed understand things better but the practical position with regard to the problem of comparing masses remains essentially the same. Thus, even now the most practical way of comparing masses is no other than that of comparing the respective weights. Having recognised that, the next problem one has to face is to define an appropriate unit which could be regarded as the fundamental universal standard of mass and to which all practical measurements of this quantity could be referred.

As has already been described in Part I, the grand scheme set out in the French law of 1799, adopted one ten-millionth part of the earth's quadrant as the fundamental unit of length. A material representation of this unit was deposited in the National Archives and given the name *Metre des Archives.* At the same time, it was decided to fix the fundamental unit of mass jointly by the dimensions of the Earth and the physical properties of pure water. The desired unit was defined as the mass of one cubic decimetre of pure water at its temperature of maximum density (which is very nearly 4°C), and the name *kilogramme* was given to it. A platinum standard intended to serve as the material representation of this unit was prepared by Le Fevre, Gineau and Febroni, and was deposited in the Archives in company with the Metre. Technically, this mass standard is referred to as the *Kilogramme des Archives.*

Incidentally, for purposes of liquid measure, the name litre was given to the volume unit of one cubic decimetre; thus, *by definition,* one litre of pure water at its temperature of maximum density had a mass of one kilogramme.

The Archives standard, however, could not continue indefinitely; it had to yield place to the so-called *International Prototype Kilogramme.* The story of this transfer of honour from one standard to the other is precisely the same as in the case of the Metre; hence, there is no point in repeating it here (see Part I). Suffice it to say that since 1889, the kilogramme is officially represented by a fundamental prototype standard which has been established at the International Bureau of Weights and Measures, Sevres. This standard is in the form of a solid cylinder (made of the Johnson-Matthey alloy), having a diameter essentially the same as its height (about 39 mm), with edges very slightly rounded. The arrangements for its preservation and for the disposal and maintenance of its copies are the same as for the Prototype Metre.

With both metre and kilogramme redefined, it became very natural to enquire if one cubic decimetre of pure water, at its temperature of maximum density, did really have a mass exactly equal to one kilogramme. Measurements showed that it was not so. In fact, the new standard of mass turned out to be 28 parts in a million greater than the mass of a cubic decimetre of pure water at its temperature of maximum density, the latter being the previous definition of the mass standard. Thus, a litre could not be:
(i) a cubic decimetre and, at the same time
(ii) the volume of one kilogramme of pure water at its temperature of maximum density.

In 1901, this conflicting position was clarified by specifically adopting the definition for the litre, so that we now have: 1 litre = 1.000028 cubic decimetre. Correspondingly, 1 millilitre (ml) is equal to 1.000028 cubic centimetre (cc). It may be mentioned in this connection that the 11th General Conference of Weights and Measures, which met in Paris in October 1960, has invited the International Committee to study and, if possible, resolve the confusing situation arising due to the aforementioned difference between two nearly equal units of liquid measure.

The Yard and the Pound

It does not appear to be out of place to make here a brief mention of the Imperial units of length and mass and of their relationship with their metric counterparts. The importance of these units lies in the fact that they are used practically in all non-metric measurements in science and technology.

Established by the British Weights and Measures Act of 1856 and explicitly defined by a similar Act of 1878, the *Imperial Standard Yard* is represented by the distance between two transverse graduation lines on a bar of square cross-section, made of bronze alloy (known as Baily's metal: 16 parts of Copper, $2\frac{1}{2}$ parts of Tin and 1 part of Zinc), when the bar is at 62°F and is supported on eight equally spaced rollers. This yard standard is preserved at the Standard Weights and Measures Department of the Board of Trade. There are five parliamentary copies as well, which are deposited with some of the premier institutions of Great Britain.

Repeated determinations, carried out by the National Physical Laboratory of England, have shown that, from the point of view of preservation of the unit of length, the British standard has been rather inferior to the French standard. This lack of reliability was one of the main reasons for the adoption, in 1959, of the so-called *International Yard,* defined (by agreement between the United States and the British Commonwealth) through the permanent definition, namely

1 yard = 0.9144 metre.

Correspondingly, we have the *Imperial Standard Pound,* which is represented by the mass of a cylinder of platinum, of diameter slightly less than its height, provided with a shallow groove round its cylindrical surface (meant for engagement with an ivory lifting fork). The arrangements for preservation and for disposal and maintenance of the five parliamentary copies of this standard are the same as in the case of the corresponding unit of length. Again, in view of some lack of reliability*, and for other reasons as well, an *International Pound* was adopted in 1959. This, through a permanent definition, equals 0.45359237 kg.

The Unit of Time

The physical reality to which the notion of time relates is so all pervasive that, it is impossible to describe any human activity without a direct or indirect reference to it. The beginning of any experiment occurs before its end and the experiment itself is assumed to occupy a certain definite time interval. Observations such as this show that, for any observer, the various physical events that take place in the universe can be arranged in an unambiguous order governed by the concepts of before, after and simultaneous. According to the German mathematician and philosopher Leibnitz (1646–1716), 'Space is the abstract of all relations of co-existence. Time is the abstract of all relations of sequence'.

Now, the primary problem of interest here consists in the selection of a standard time-keeping device, with reference to which the duration of any particular time interval could be reliably ascertained. Such a time-keeper could very well be the rotation (or revolution) of the Earth, the oscillation of a free pendulum or of a flat spiral spring, the emission of radiation by an atomic system, or the vibration of a crystal of quartz. The most essential prerequisite for the intended purpose would, of course, be that the assumption of the constancy of recurrence interval of the periodic process involved be strictly valid.

From the very earliest of times the rotation of the earth on its axis has been the most obvious choice as the common standard of time-keeping. It has indeed proved to be a very good choice. In this connection, we have, first of all, the solar day, which is reckoned as the interval between two successive transits of the sun across the meridian; this, however, varies throughout the year. The astronomers, therefore, introduced the so-called *mean solar day;* this was defined in reference to a fictitious sun 'moving' uniformly through the 'fixed' stars, the speed of motion being equal to the average speed of the true sun. The fundamental unit of time the *second* was then defined as 1/86400 of a mean solar day.

Obviously, any time system based on the rotation of the Earth will be uniform only if the rate of rotation is itself uniform. However, it is now known that this condition is not strictly fulfilled. Using quartz clocks (to be described a little later) as time-standards, the period of rotation of the Earth has been found to show seasonal variations of the order of microseconds. There is also a secular variation caused possibly by tidal friction. It has been estimated that our astronomical unit of time has varied during the last hundred years by about 7 parts in 10^8 (there is, of course, good evidence that during a year the unit is uniform to about 4 parts in 10^9).

*It may be mentioned here that certain pound–kilogramme comparisons carried out at the British NPL, during the period 1960-61, showed that the Imperial Standard Pound had increased by about 1 part in 10^7 since 1932, when this comparison was last made.

Accordingly, a new time-standard, called the *Ephemeris Time,* has been adopted; this one is based on the period of revolution of the earth around the Sun. Unfortunately, this again is not strictly constant; hence, the length of a specific year has been chosen. Thus, on 14 October, 1960, the 11th General Conference of Weights and Measures confirmed the action of the International Committee of Weights and Measures in replacing the older definition of the second by redefining it as 1/31556925.9747 of the tropical year 1900. This decision effectively freezes the definition of the second in terms of the mean solar day of the year 1900, and so makes it independent of the secular changes in the Earth's motion. It should be noted that it is only the *second* of the ephemeris time that is now to be referred to as the second. Further, it appears of interest to point out that the new second is shorter, by about 2 parts in 10^8, than the previously defined second (as pertaining to the present epoch); this, however, does not raise any practical questions about the continuity of usage.

In contrast to the standards of length and mass measurement, the second obviously cannot be kept in safe deposit with any institution, its relation to the current measures of time has got to be secured only by means of tables cataloguing the apparent motion of the sun. In practice, it is more convenient to make observations on the Moon and employ a lunar ephemeris (table of the predicted positions of the Moon) accurately related to the calculated motions of the Sun.

The Laboratory Standards of Time-Keeping

It would, of course, be preferable if one could have a time standard based on a mechanism which is easily reproducible and at the same time, sufficiently reliable. For this, an atomic clock immediately comes to mind. Such a clock is a means of measuring time intervals in terms of the characteristic periods of certain molecules or atoms. As is well known, the transition between the energy states E_1 and E_2 of an atomic system is accompanied by the emission (or absorption) of radiation having a frequency given by $h\nu=(E_2-E_1)$, where h is Planck's constant. Any spectral line thus provides a frequency ν which is a physical constant; of course, to be useful as a standard it must fall in the range of frequencies which can be related to the laboratory oscillators or clocks, and it must be of a sufficiently precise determination and definition.

Now, time-keepers based on the quartz-crystal oscillators have also been in use for quite some time. These clocks operate with such a uniformity of rate that their inter comparisons can be made with a precision of about 1 part in 10^{10}. Two standard quartz clocks are maintained at the British NPL, where much of the pioneer work in their development was done. At the same time, an atomic clock based on the frequency of a particular spectral line of caesium has also been developed there. The comparison between the quartz clock and the atomic clock has also been carried out with an accuracy of about 1 part in 10^{10}; the final mean value for the frequency of the caesium line in question comes out to be 9.19263177×10^9 per (ephemeris) second. This frequency, being a fundamental atomic constant, is practically unaffected by external conditions.

It is estimated that it would take about ten years of astronomical readings to reduce measurements of the second to an accuracy of 5 parts in 10^{10}. Hence, the implementation of the official definition of the Ephemeris Standard appears to require the use of at least atomic clock standards. One rather hopes that ultimately the ephemeris second will itself be replaced by an 'atomic' second, defined in terms of the period of an atomic clock, such as the caesium clock. In this connection, the understandable reluctance to break with a practice as old as civilisation has got to be appreciated. But a consideration of the precision of measurements and the necessity of ready reproduction of standards alone shows that the present unit of time may not for long remain suited for advanced measurements of frequencies and time intervals.

PART III

In the preceding articles of this series the three fundamental units of measurement in mechanics, namely the metre, the kilogramme and the second were dealt with. In this article, we pass on to the realms of heat and light. In the case of heat, we have to discuss the fundamental units employed in thermometry and calorimetry, and in the case of light the fundamental units employed in photometry.

The Measurement of Temperature

By far, the most basic concept in the study of heat and thermodynamics is that of temperature. The practical basis for the measurement of temperature is provided by the so called zeroth law of thermodynamics; which states that—*two bodies (or systems) which are in thermal equilibrium with a third one are in thermal equilibrium with each other.* Since one of these bodies could be some sort of a thermometer, the temperature of any given body may be determined by establishing thermal equilibrium between it and a thermometer. For an unambiguous expression of the result of such a measurement, we need what is called a *temperature scale.*

The fundamental principles of thermodynamics, which developed through the pioneering work of Carnot (1796–1832), Clausius (1822–1888) and Kelvin (1824–1907), led to a *temperature scale* which is entirely independent of the properties of any particular substance in Nature. This scale, defined in terms of the quantities of heat associated with a Carnot cycle, is known as the thermodynamic scale of temperature and is recognised as the ideal scale to which all temperature measurements should ultimately be referable. In principle, this scale could be realised rather simply by means of an ideal gas thermometer; in practice. However, neither the gas nor the thermometric procedure actually available is ideal enough for the purpose. Cumbersome corrections for these imperfections have got to be applied before the actual results can be adopted with security.

The experimental difficulties inherent in the precise measurement of temperature on the thermodynamic scale using real gas thermometers as well as the need for an easily and accurately reproducible practical temperature scale, led to the introduction of an *International Temperature Scale (ITS).* This (practical) scale was first adopted by the 7th General Conference on Weights and Measures, held in 1927, and its declared aim was to provide a scale which followed as closely as possible the thermodynamic centigrade scale realisable at that time. The 1927 scale was revised in 1948 with a view to obtaining the closest possible agreement with the thermodynamic scale in the light of the new knowledge gained and including slight modifications (based on experience) so as to render the scale more uniform and reproducible than its original version. The revised scale, known as the *International Temperature Scale of 1948 (Int. 1948)*, was adopted by the 9th General Conference in October 1948.

The 1948 scale was based on six fixed points (including the two fundamental fixed points), to which definite numerical values (in °C) were assigned. These values, in each case, defined the equilibrium temperature corresponding to a pressure of one standard atmosphere (equal to 1,013,250 dynes cm^{-2}). These fixed points were as follows:

Temperature °C	
1. Boiling point of oxygen (the oxygen point)	–182.9700
2. Melting point of ice (the ice point)	0
3. Boiling point of water (the steam point)	100
4. Boiling point of sulphur (the sulphur point)	444.600
5. Freezing point of silver (the silver point)	960.8
6. Freezing point of gold (the gold point)	1063.0

The ice point and the steam point were the two fundamental fixed points, whose assigned values were meant to be exact. In the case of the remaining four points, the so called 'primary' fixed points, the last decimal place given for each of the values only represented the degree of reproducibility of that point.

The means available for interpolating temperatures over the whole range of practical interest led to the division of the scale into four parts, using three different instruments for interpolation. These were defined as follows:

(a) The temperature region from the oxygen point to the ice point was defined by means of a standard (platinum) resistance thermometer, using a quartic formula;

(b) The region from the ice point to the freezing point of antimony (630.5°C), again by means of a standard resistance thermometer, but using a quadratic formula;

(c) The region from the freezing point of antimony to the gold point, by means of a standard (platinum, rhodium-platinum) thermocouple with the cold junction of the couple at 0°C and

(d) The region above the gold point, by means of a radiation pyrometer, using Planck's radiation formula.

The 1948 Conference also made a number of recommendations regarding apparatus, methods and procedures to be adopted in the realisation of the scale. For details, reference may be made to sources listed at the end.

It is important to mention here that besides the fundamental and primary fixed points, the 1948 scale also admitted as many as 22 'secondary' fixed points. The highest one in the list being the melting point of tungsten (3380°C). The temperatures assigned to these points were given in terms of the International Scale defined by the six aforementioned points and the associated interpolation formulae. These secondary points were intended to be used as additional reference points on the scale and, hence, could serve a pretty useful purpose in practice.

An interesting, and also somewhat revolutionary, step was taken by the 1948 Conference in adopting a new adjective for the degree on the temperature scale. The word 'centigrade' was discarded in favour of 'Celsius'. Thus, henceforth one had to read 56°C as 'fifty-six degrees Celsius' and not 'fifty-six degrees centigrade'.

In defence of the foregoing decision to change such a firmly established nomenclature, it may be stated that it was Anders Celsius (1701–1744), a Swedish astronomer, who was the first to divide, in 1742, the fundamental interval between the ice point and the steam point into 100 parts. This name has already been in general use in Germany and some other countries for many years, the symbol fortunately being the same, namely °C. Moreover, unlike the rival scales named after their originators, Fahrenheit (1686–1736) and Réaumur (1683–1757), this scale was the only one which did not perpetuate the name of the man who first visualised it.

The Thermodynamic Scale

From a fundamental point of view, it is quite clear that howsoever dependable an empirically established scale may be, we must not lose sight of our ultimate goal, the thermodynamic scale. One unique feature of this scale is the existence on it of a naturally fixed point, namely the absolute zero. Then, in principle, the specification of only one more point on the scale would define it completely, for the scale, as visualised, is a linear one. This position was specifically emphasised, in 1854, by Lord Kelvin, who was the first to suggest this ideal scale, defined solely through the ice point; the suggestion was repeated 20 years later by Mendeleev (1834–1907) and again in 1939 by Giauque (b. 1895).

Now, the 1948 Conference had already recognised that, with the experimental technique as is generally available, the triple point of water (namely the temperature at which its three phases co-exist) promises to be a much more precise thermometric point than the ice point. Subsequent laboratory work strengthened this view all the more, with the result that the 10th General Conference, which met in 1954, resolved to define the thermodynamic scale by means of the triple point of water as the (sole) fundamental fixed point, by assigning to it the temperature 273.16°K exactly. The degrees on this scale were designated to perpetuate the name of Lord Kelvin, who had visualised such a scale exactly one hundred years previously.

We then have two alternative scales, namely the *International (Celsius) Scale of 1948* and the *Thermodynamic (Kelvin) Scale.* From any given temperature on the former scale, we can obtain, by adding 273.15, a temperature which is referred to as the *International Kelvin Temperature,* °K (Int. 1948); this provides an almost exact representation of the given temperature on the Thermodynamic Scale. Similarly, from any given temperature on the latter scale, we can obtain, by subtracting 273.15, a temperature which is referred to as the *Thermodynamic Celsius Temperature,* °C (therm.); this again provides an almost exact representation of the given temperature on the International Scale of

1948. The correspondence, however, is only approximately exact, for the reason that while one of the scales puts the ice point exactly 273.15 degree above absolute zero, the other puts the triple point of water exactly 273. 16 degree above absolute zero. It is, then, natural that the size of the degree on one scale is some what, though only very slightly, different from that on the other. This difference, however, has got to be investigated more thoroughly before its detailed practical implications are fully realised. Meanwhile, with any declared temperature it is essential to specify as to which of the scales was originally employed.

It may be noted that, with a view to bringing about further improvements in the International Scale of 1948, the 11th General Conference of 1960 has made the following modifications:

4. The scale has been renamed the *International Practical Scale of Temperature,* 1948; the introduction of the word 'Practical' is worthy of note.

5. The triple point of water has been made one of the defining fixed points of the scale, with a temperature of 0.01°C (Int. 1948), while the ice point has become a secondary fixed point, with the value 0.000°C.

6. The distinction between the fundamental fixed points and the primary fixed points has been dropped and one now refers to all of them as fixed points by definition.

The 1962 meeting of the International Committee on Weights and Measures has also made a number of tentative proposals for presentation at the 1966 General Conference. These proposals are intended primarily,

(a) to extend the range of the Practical Scale below the oxygen point, and

(b) to improve the accuracy of this scale by revising some of the values assigned to its fixed points.

Limitations of space do not permit the inclusion of an account of these proposals here; the interested reader is referred to a report which appeared in *Nature*: 197, 1055, 1963.

The Unit of Heat

Since the very beginning of calorimetry, water has been used as a standard material for heat capacity measurements. This has been partly due to the fact that it happens to be a very convenient substance for study at ordinary temperatures and partly because it is universally available in a pretty high degree of purity. Consequently, the earliest unit of heat was defined in terms of the quantity of heat required to raise the temperature of a known mass of (liquid) water through a known range of temperature. For instance, the so-called *calorie* was defined as the quantity of heat required to raise the temperature of one gramme of pure water through one degree centigrade (henceforth to be called degree 'Celsius').

As heat measurements increased in precision, it became clear that in order to be unambiguous it was necessary to specify the mean water temperature (or the relevant interval of temperature) while defining the calorie. This specification gave rise to a number of slightly differing calories, such as the 15°C *calorie* ($cal_{15°}$) which refers to the rise in temperature from 14.5°C to 15.5°C, the *maximum density calorie* ($cal_{4°}$) which refers to the rise from 3.5°C to 4.5°C, the 20°C *calorie*

($cal_{20°}$) which refers to the rise from 19.5°C to 20.5°C, and the *mean calorie* (cal_{mean}) which was defined as the 100th part of the quantity of heat required to raise the temperature of 1 gramme of pure water from the ice point to the steam point. Calorie, one or the other, is thus the basic 'caloric' unit of heat.

As is well known, it followed from the work of Rumford (1753–1814) and Davy (1778–1829), that heat originates from motion and, in consequence, is only another form of energy. The physical equivalence between work and heat was finally and unequivocally established by the remarkably accurate experiments of Joule (1818–1889). Through electrical as well as mechanical experiments, Joule was able to determine the so called Joules equivalent of heat, which defines the quantitative relationship between the amount of work (mechanical or electrical) expended and the quantity of heat produced. In terms of the absolute unit of work, which derives directly from the metre-kilogramme-second system of mechanical units or from the relevant electrical units (see IV in the next issue), namely the *joule,* we have the following relationships (as they presently stand):

1 $cal_{15°}$	=	4.1855 joule,
I $cal_{4°}$	=	4.2045 joule,
I $cal_{20°}$	=	4.1816 joule,
1 cal_{mean}	=	4.1897 joule.

The 1948 General Conference, however, recommended that the quantities of heat be expressed directly in terms of the energy units (rather than the 'caloric' units), and to this end adopted joule as the basic unit of heat. Of course, their resolution was appended by the remark that, if the experiments have been made by comparison with heating of water (and if for any reason the use of the calorie cannot be avoided), then all the information necessary for conversion into joules should be furnished. For this purpose, it was suggested that the International Committee establish a table which will present the most precise values of the specific heat of water, at various temperatures, in joules per degree Celsius The desired table was prepared by de Haas and was accepted by the International Committee in 1950; it is available on p. 56 of the 1959 edition of the Kaye and Laby Tables.

In view of the 1948 decision, the International Conference on the Properties of Steam, held in London in 1956, redefined caloric the so-called I.T. *calorie* (cal_{IT}) as an exact multiple of the Joule, thus rendering it independent of temperature. The resulting unit, employed mainly by steam engineers, was also recommended by the British Standards Institution in 1959; it is, by definition, equal to 4.1868 joule exactly. Furthermore, we have the *defined thermo-chemical calorie,* used mainly in the U.S.A., which was defined in 1948 to be equal to 4.184 joule exactly.

In this connection, it is worthwhile to note that these days most investigators concerned with calorimetry make measurements directly, or almost directly, in terms of the absolute electrical units. For them, it is obviously simplest and best to express their results in joules rather than in calories. Habit, however, causes many to stick to their old inconveniences, so until these habits go we will continue to see the caloric used. Of course, we do look forward to the time when the use of the joule in this field will be quite general.

The Unit of Luminous Intensity

Next, we consider the international unit relevant to the domain of photometry, i.e. the evaluation of light. The quantity fundamental to this subject is the 'luminous flux', which is a measure of the resultant physical effect of the radiant flux on the eye. The luminous flux is measured in terms of the unit called lumen (lm) which is defined as the luminous flux emitted within a unit solid angle by a uniform source of luminous intensity unity*. We then have to deal with the quantity 'luminous intensity' which derives from the flux to describe the strength of a light source in regard to its ability to produce illumination.

The unit employed for expressing the luminous intensity of any given light source has, up till 1948, been the so-called *International Candle.* This was originally defined in terms of a candle of specified composition. However, in 1909, it was re-defined in terms of certain special lamps (the Carcel and pentane lamps), but was maintained by a set of carbon filament electric lamps. Unfortunately, this mode of maintenance has proved incapable of the desired degree of reliance in reproduction. With this in view, the International Committee on Weights and Measures adopted, in 1948, the black-body radiator as a standard source for this purpose. Thus, they defined a new unit of luminous intensity, named the *candela* (cd), such that one square centimetre of the surface of a black-body radiator at the temperature of solidification of platinum (2046°K) has a luminous intensity of 60 cd in the direction normal to the surface; in other words, the radiator surface has a luminance of 60 cd/cm^2. One finds that the new unit is approximately 0.98 of the original International Candle.

The main standardising laboratories now employ a special arrangement, shown in Fig. 1, for the realisation of the candela. This arrangement consists of a small cylinder of pure fused thoria about 45 mm long and of internal diameter about 2.5 mm. Its bottom is packed with

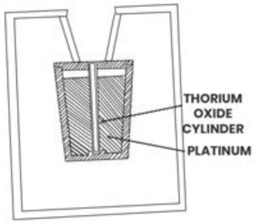

Fig. 1

powdered fused thoria about 10 mm deep. It is supported in a crucible of fused thoria containing platinum. The hole in its lid acts as the black-body radiator. The crucible is surrounded by powdered fused thoria. The platinum is melted by placing the crucible in the coil of a high frequency induction furnace. The power is then reduced until the heat supplied is slightly less than that lost to the surroundings. The platinum thus cools slowly and maintains the cylinder at its melting point, whilst this is solidifying and giving out its latent heat of fusion. This condition can be maintained for about 10 minutes, the constancy of the temperature being indicated by the luminance of the radiator remaining constant.

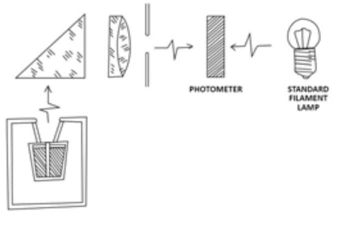

Fig. 2

*It may be noted that for the wavelength corresponding to the maximum visual sensitivity, namely 5550 Å, one watt of monochromatic light is equivalent to 686 lumens: See Gillham, E.J. 1964, *Proc. Roy.Soc. London,* **A 278:** 137

When in use, the crucible is mounted near a photometer bench and an enlarged image of the radiator is formed on a photometer by means of a lens and prism (see Fig. 2). Viewed from the photometer, the lens diaphragm appears filled with light, and this has the same luminance as the radiator (except for transmission losses, which can be ascertained by an auxiliary experiment). Thus, the area of the hole in the radiator need not be known. Then, by the customary photometric procedure the luminous intensity of filament lamp standards is compared with that of the radiator, effecting thereby the calibration of the sources actually used in practice.

PART IV

The C.G.S. Systems of Electrical Units

The present story starts with the pioneering work of Gauss (1777–1855) and Weber (1804–1891), which for the first time indicated the possibility of measuring electrical (including magnetic) quantities in terms of the fundamental, mechanical units of length, mass and time, and one additional electrical quantity. In 1863, a British Association Committee, working under the chairmanship of Clerk Maxwell (1831–1879), recommended the adoption of a system of electrical units based on the centimetre, the gramme, the second and the additional quantity, viz., the magnetic permeability of *free* space, which was arbitrarily assigned the numerical value unity. Through a subsequent endorsement of this recommendation, by the International Electrical Congress of 1881, this system acquired the necessary official status for international adoption and came to be called the *c.g.s. electromagnetic* system of units or else the *'absolute'* system of units. On this system, magnetic pole strength (a theoretical concept not susceptible of physical realisation) corresponds to the experience of a unit force (1 dyne) of repulsion between two identical poles separated by a unit distance (1 cm) in free space. Proceeding from this definition of the unit pole strength and making use of the various derived units of mechanics (the unit of force, the unit of energy, etc.) one can develop a consistent scheme of units, *by definition,* for all the quantities appearing in the domain of electromagnetics.

There was, however, one great disadvantage of the foregoing system, namely, that the magnitudes of the resulting units were not convenient for *practical* use. The 1881 Congress, therefore, set up a limited number of so-called practical units, which were defined as certain appropriate multiples or submultiples, in powers of 10, of the 'absolute' units and were named after some of the distinguished workers in the field. These were:

1 Ampere = 10^{-1} 'absolute' unit of current,

1 Coulomb =10^{-1} 'absolute' unit of charge,

1 Volt = 10^{8} 'absolute' units of potential difference,

1 Ohm = 10^{9} 'absolute' units of resistance, and

1 Farad = 10^{-9} 'absolute' unit of capacity.

In 1889, there followed two more practical units, namely,

1 Joule = 10^{7} ergs, and

1 Watt = 10^{7} ergs/sec,

while in 1893 was defined the practical unit of inductance.

1 Henry = 10^9 'absolute' units of inductance.

A second disadvantage of the c.g.s. electromagnetic system of units was that its use in electrostatics appeared somewhat unnatural and artificial. So, a parallel system of units came into being, for which the additional quantity to form the fundamental basis was taken to be the electric permittivity of *free* space, with the assigned numerical value unity. This system was designated as the *c.g.s. electrostatic* system of units. On this system, the unit electric charge is, by definition, that charge which repels an identical charge situated a unit distance (1 cm) away in free space with a unit force (1 dyne). Again, proceeding from this definition of the unit charge and making use of the various derived units of mechanics, an equally consistent, and complete, scheme of units, *by definition,* can be developed.

In view of the assumption of free space having a unit permeability in the first case and a unit permittivity in the second, the relationships between the corresponding units in the two systems involve certain powers of C, the velocity of light in free space in cm/sec, i.e. approximately 3×10^{10}. For instance,

1 e.m. unit of charge/current $\approx 3\times10^{10}$ e.s. units of charge/current,

1 e.m. unit of potential difference $\approx \frac{1}{3\times10^{10}}$ e.s. unit of potential difference,

1 e.m. unit of resistance $\approx \frac{1}{(3\times10)^2}$ e.s. unit of resistance

1 e.m. unit of capacity $\approx (3\times10^{10})^2$ e.s. units of capacity, and so on.

From these relationships one can easily obtain the relevant conversion factors between the e.s. units and the practical units. We note that the two systems of units, viz., the c.g.s. electromagnetic and the c.g.s. electrostatic, can be used either separately or as component parts of the mixed *Gaussian* system. Of course, strictly speaking, this scheme does not constitute a basic system of units as such; it is merely an arrangement of using the two basic systerns *together.* Here, all those quantities which are predominantly magnetic in character are expressed in the e.m. units while those which are predominantly electrical in character are expresed in the e.s. units. The balance in the physical equations is achieved by the insertion therein of appropriate conversion factors, which are invariably certain powers of the fundamental constant C.

The International Units and the Electrical Standards

Although electrical quantities can somehow be related to the units of length, mass and time, electrical measurements based upon these relationships—the so-called 'absolute' measurements—are quite cumbersome and time-consuming. On the other hand, measurements involving inter-comparisons of the corresponding electrical quantities are relatively straight-forward and capable of much better accuracy. Naturally, therefore, it appeared desirable to establish some sort of international standards of the leading electrical quantities, so that all subsequent electrical measurements in the laboratory could be made in direct (or indirect) reference to these standards.

With this end in view, the International Conference of Electrical Units and Standards, held in 1908, defined a system of *International Units* which were intended to be as close in value as possible to the 'absolute' practical units defined earlier but based on certain suitably chosen material standards. These were defined as follows:

'The *International Ohm* is the resistance offered to an unvarying current by a column of mercury (at the temperature of melting ice), being 14.4521 g in mass, of constant cross-sectional area and of length 106.300 cm.'

'The *International Ampere* is the unvarying current which, when passed through a solution of silver nitrate in water (in accordance with standard specifications), deposits silver at the rate of 0.00111800 g/sec.'

However, in view of the practical difficulties encountered in the silver voltameter measurements, the committee also recommended the use of a specified Weston cell as a convenient standard of electric potential difference. The relevant unit defined in terms of this cell, namely the *International Volt*, could in turn be combined with the international unit of resistance to define the corresponding unit of current. Even for the resistance standard, it was deemed preferable to employ certain specially designed manganin coils rather than a Mercury column.

Now, in order to ensure the uniformity of the electrical standards, comparisons on an international scale are clearly necessary.

Firstly, this would enable one to record the drifts in values which the standards maintained by the various laboratories show with time. Secondly, one could take the mean of the values for a particular standard, as obtaining in different laboratories, as the Mean International Unit of the corresponding quantity; of course, for the stability of the defined units, the Mean Units could not be allowed to drift much with time.

Such comparisons began in 1910, and continued till 1948 (beyond which there remained no need to go). In the 1910 comparisons, made at Washington, standard resistors and cells from Britain, France and Germany were compared with the corresponding American standards. An elaborate series of silver voltameter experiments was also carried out, but the results were found to vary a lot with the type of voltameter used. These results were, of course, helpful as a guide in assigning the numerical values to the e.m.f. of the Weston cells. The mean value of the e.m.f. for 104 Weston cells studied was found to be 1.0183 international volts. This value was accordingly assigned to the e.m.f. of the Weston Standard Cell.

With a view to improving international cooperation the 6th General Conference on Weights and Measures, meeting in 1921, gave its International Bureau at Sevres the duty of establishing standards of the electrical units and comparing these with the national standards. The Bureau accordingly maintained a group of standards originating from the various national laboratories. Groups of duly standardised standards were also maintained by a number of leading laboratories of the world. Nevertheless, the periodic comparisons went to show that the values of the units obtaining in different laboratories continued to have variations of a few parts in 10^5.

Reversion to the 'Absolute' Units

As it has already been pointed out, the absolute electrical measurements involved a lot of practical complications and demanded a lot of time and effort of the investigator.

That indeed was the major reason why resort had to be made to the so called International Units and Standards. In principle, however, we ought to somehow realise our electrical standards directly in terms of the mechanical units, so that there no longer remains a need of maintaining any material reference standards. It took some few decades before the ground was ripe for this. In fact, as the technique of measuring the 'absolute' units further progressed, a stage was reached, by 1930, when the 'absolute' *Ohm* and *Ampere* could be realised as accurately as their international counterparts. Then, there was left nothing to be gained by retaining the latter.

This was the patent view of the 8th General Conference on Weights and Measures, which met in 1933. They indeed visualised a change-over from the international to the 'absolute' units by just about 1940, thus allowing sufficient time for the ratios between the units of the two systems to be accurately determined. This process, however, got considerably delayed by the World War II, and eventually came about only in 1948. Meanwhile certain other developments had taken place which sought for another change-over, namely one from the c.g.s. units of mechanics to the so-called m.k.s. units. The 1946 International Committee on Weights and Measures took momentous decisions, becoming effective from 1st January 1948, which not only incorporated both these changes into a single scheme but also gave rise to a most satisfactory system of electrical units. For a proper appreciation of this transformation, it becomes necessary to re-narrate our story, starting once again from the turn of the century but keeping to a track different from the previous one.

In the wake of the introduction of a number of practical units, during the period 1881–1893, there resulted much discussion about the need for an early completion of the practical system, so that the continued use of the mixed (Gaussian) set of units could be avoided. The most fruitful suggestion in this direction came from Professor Giorgi of Rome who in 1901, proposed a new system of units, which was placed for consideration before the International Electrical Congress of 1904. In this system, the metre replaces the centimetre, the kilogramme replaces the gramme, the second remains as such, while the magnetic permeability μ_0 of free space is chosen to be a dimensional constant with numerical value different from unity. The derived units of energy and power in this system turn out to be the practical ones, namely the *joule* (=10^7 ergs) and the *watt* (=10^7ergs/sec), respectively. The unit of electric current can, using Ampere's law, be defined in terms of: (i) the force of interaction between two parallel, infinitely long, current-carrying conductors, (ii) their distance apart, and (iii) the permeability of the medium in between. The relevant formula for the force experienced per unit length of either conductor is:

$$F = 2\mu\, I_1 I_2/r \qquad (1)$$

where the symbols have their usual meanings.

Let us now recall that for such a pair of conductors the interaction force, in dynes/cm, for a flow of 1 e.m. unit of current in either of them, with a separation *in vacuo* of 1 cm, is equal to 2. Obviously, then, the interaction force, in newtons/m, for a flow of 1 'absolute' ampere (=1/10 c.m. unit) of current in either of them, with a separation *in vacuo* of 1 m, would be 2×10^{-7}. Thus, the 'absolute' ampere would become the natural unit of current in the Giorgi system provided that we assign a value of 10^{-7} to μ_0. On then follows the natural sequence of units:

(i) the coulomb as the unit of charge, being the amount of electricity transported in 1 sec by a current of 1 ampere;

(ii) the volt as the unit of potential difference, being the difference of electric potential between two points of a conducting wire carrying a current of 1 ampere when the power dissipated between these points is equal to 1 watt;

(iii) the ohm as the unit of electric resistance, defined in terms of the volt and the ampere or in terms of the rate of dissipation of heat (in joule/sec *or* watt) due to the passage of an ampere of current through the resistor;

(iv) the farad as the unit of capacity, defined in terms of the coulomb and the volt; and so on.

The system of units suggested by Giorgi, with $\mu_0=10^{-7}$ (henry/m)*, is thus possessed of the supreme merit of having the 'absolute' practical units as the very natural and fundamental units of the system itself. His suggestions, therefore, deserved a very sympathetic and serious consideration; however, for a period of over thirty years since the suggestions were first made, nothing tangible came out.

It appears worthwhile to point out here that, instead of proceeding on the basis of the Ampere law, one could as well make a start by defining the unit of charge. On the basis of the Coulomb law of force between electric charges at rest, namely,

$$\text{Force of interaction} = \frac{q_1 q_2}{\epsilon r^2} \qquad (2)$$

where ϵ denotes the electric permittivity of the medium concerned. Now, we know that 1 e.s. unit of charge experiences, when situated at a distance of 1 cm from an identical charge *in vacuo,* a force of 1 dyne. Obviously, then, 1 'absolute' coulomb (= c/10 e.s. units) of charge would experience, when situated at a distance of 1m from an identical charge *in vacuo,* a force of approx. 9×10^9 newtons. Thus, the 'absolute' coulomb would become the natural unit of electric charge provided that we assign a value of approx. $1/(9 \times 10^9)$ to ϵ_0, the permittivity of *free* space; one can readily verify that the relevant unit for E, would be farad/m*. Indeed, the numerical value of the quantity $1/(\mu_0 \epsilon_0)^{1/2}$ is approx. 3×10^8, the free-space velocity of light in m/sec.

We thus see that a fully self-consistent scheme of electrical units is obtained by adopting the three m.k.s. units of mechanics, along with a fourth (electrical) unit, such as the ampere (realised by assigning a definite value to μ_0 and making use of the Ampere law) or the coulomb (realised by assigning a definite value to ϵ_0 and making use of the Coulomb law). In terms of the basic set of four units, one can define *quite unambiguously* the whole multitude of units met with in electricity and magnetism. Of course, the simplicity lost in achieving this end is more than obvious from the unwholesome values attributed to the properties μ_0 and ϵ_0, of the free space. One may, however, look at these values simply as certain constants of nature the so-called '*magnetic* and *electric* space constants'

*it may be noted that this value of μ_0 is exactly the equivalent of 1 em unit of inductance/cm.

just as we have the constant of gravitation G. It must be clearly stated that the manner in which the values of these two constants have been treated as adjustable is, speaking from first principles, no more arbitrary than the process of adopting the fundamental units themselves.

Well, it was only in 1935, that the International Electrotechnical Commssion resolved to adopt, in principle, the aforementioned Giorgi system of units, and even recommended that this should be the name of the system. However, in a number of countries, it had earlier been called the m.k.s. system, and this terminology has persisted. Of course, a more appropriate designation would be the 'm.k.s.a. system', indicating as well the fourth unit, which was finally chosen to be the ampere, as an integral part of the basis for this four-dimensional system.

The Rationalised Units

Having evolved a system of units possessing the desired property of leading, in quite a natural manner, to units which are, by and large, identical with the ones employed in practice, we had to face yet another problem in this field. This problem, commonly known as the 'rationalisation' of the system of units employed, is no doubt much less fundamental than that of the evolution of the system itself. Plainly speaking, it does not at all constitute a matter of necessity; it is primarily of an aesthetic and/or intuitive origin. It started with the English physicist Oliver Heaviside (1850–1925), who actually waged a life-long battle over it, from the simple observation that in the electromagnetic equations and formulae the factor (4π) appears at rather inappropriate places and it does not appear where it might be expected to. For example, one would expect it to appear in the formulae relating to problems involving spherical (or cylindrical) symmetry, and not in those involving planar symmetry. However, very often the actual situation is the very reverse of this; recall, for instance, the formulae for the capacity of cylindrical and parallel-plate condensers, etc. A situation like this appeared quite *irrational* to anyone who looked at things the way Heaviside did.

It was specifically pointed out by Heaviside that the foregoing defect could be remedied by inserting an additional factor of $1/(4\pi)$ on the right-hand side of the Coulomb law. This would restore the factor (4π) to places where it is expected to be and remove it from places where it stands unwanted. Among the typical changes this modification brings about in the formulae of electromagnetics, two major ones are the disappearance of the factor (4π) from Maxwell's equations for the electromagnetic field and also from the statement of Gauss's theorem.

Lorentz (1853–1928), the famous Dutch physicist, was so much impressed by the foregoing proposal that he readily adopted it and, in consequence, chose to modify the unit of electric charge by a factor of $\sqrt{4\pi}$; this would indeed leave the value of $\in_0$, and hence of μ_0, as well, unchanged. However, one can readily see that if one finds it obligatory to modify the expression for the Coulomb law, as suggested by Heaviside, to

$$\text{Force of interaction} = \frac{q_1 q_2}{4\pi \in r^2} \qquad \text{(2-a)}$$

it is best to combine the new factor with the permittivity of the medium rather than with the charges involved. For, this way, we would cause a minimum of disturbance in the Giorgi scheme of units. In relevance to (2-a), then, the permittivity $\in_0$ of the free space would be approximately $10^{-9}/$

(36π) farad/m. At the same time, the Ampere law (1) would have to be written as:

$$F = \frac{\mu I_1 I_2}{2\pi r} \qquad (1\text{-a})$$

with the permeability μ_0 of the free space exactly equal to $4\pi \times 10^{-7}$ henry/m. It may be mentioned here that with this mode of 'rationalisation', as the process has come to be called, it is only the units of the magnetic field strength H, the electric displacement D and their derivatives (such as the magnetomotive force, etc.) whose magnitudes get changed by the factor (4π); all the basic units of the system, such as the ampere, the coulomb, the volt, etc. remain unchanged.

Needless to say that, in principle, any system of units, the c.g.s. electromagnetic, the c.g.s. electrostatic, the Gaussian, or the Giorgi, could be had in the rationalised as well as the unrationalised form. It is, however, only in the case of the last one of these that the rationalised form has attracted particular attention.

The Final Decision

The 1935, resolution of the International Electrotechnical Commission, which sought to adopt the Giorgi system of units, was confirmed by the International Committee on Weights and Measures in 1946. This Committee held that from 1 January 1948, the official system of electrical units should be the so called 'absolute' system of units, based upon the m.k.s. mechanical units, with a defined permeability of free space as 10^{-7}units. The decision concerning rationalisation was, for the time being, kept pending. For a short period, both the rationalised and the unrationalised forms of the Giorgi system were in use, but in 1950, a decision was made in favour of rationalisation, the magnetic (free) space constant then being $4\pi\times10^{-7}$ units*. Further, it was resolved that the magnetic space constant is to be realised by way of current, i.e. with the help of the modified Ampere law (1-a), holding that one ampere is that unvarying current which, when maintained in two parallel, rectilinear, conductors of infinite length and of negligible cross-section and separated by a distance of 1 metre *in vacuo*, would produce between these conductors a force of 2×10^{-7} newton per metre of length. Of course, in standardising laboratories, the actual equipment with which the 'absolute' unit of current is realised in practice is a precision current balance.

It appears of interest to mention here that at the time of adoption of the 'absolute' electrical units, in supersession to the international ones, the relationships between the two sets were given as under:

1 international ampere = 0.99985 'absolute' ampere

1 international ohm = 1.00049 'absolute' ohm,

whence it follows that

1 international volt = 1.00034 'absolute' volt,

and so on for other related quantities.

Thus, we finally have a rationalised system of 'absolute' units, emulating so satisfactorily the set of practical units, which is based on the metre, the kilogramme, the second and the ampere; hence the name 'rationalised

*It may be mentioned in passing that in this very meeting the unit of force, equalling 10^8 dynes, was designated as the *newton.*

m.k.s.a. system of units'. The associated values of the free space constants are:

$$\mu_0 = 4\pi 10^{-7} \text{ henry/m and}$$

$$\epsilon_0 \approx \frac{10^{-9}}{36\pi} \text{ farad/m}$$

Since 1950, great strides have been made in adopting the new system of units, with the result that at present it is almost universally employed in the electrical engineering works, and is widely used in textbooks concerned mainly with the domain of electricity and magnetism.

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