Chapter 4
The *Système International D'Unités* (SI) of 1960

Abstract The international metrology institutions founded by the Metre Convention became involved in other aspects of measurement of interest to science. At the time it established the international prototypes of the meter and kilogram, it was already interested in temperature scales. In the twentieth century, electrical units also came under its purview. In 1960, the 11th CGPM (*Conférence générale des poids et mesures*, or General Conference of Weights and Measures) introduced the *Système international d'unités* (International System of Units, SI) based on six base units: the meter, kilogram, second, degree Kelvin, ampere and candela. This chapter outlines some of the events that led to the introduction of the SI. Then it briefly goes back in time to sketch histories of the base units that were not part of the original metric system, namely the second, the degree Kelvin, the ampere and the candela.

4.1 The International Metrology Regime to the Establishment of the SI

The newly established international metric institutions worked initially on characterizing and measuring the materials to be used in the new metric standards. For example, knowing the thermal expansion coefficient of the platinum-iridium alloy was necessary to know how the length of a standard changed with temperature. That in turn required accurate and standardized temperature measurements.

In 1887 CIPM (*Comité international des poids et mesures*, or International Committee of Weights and Measures) adopted as a standard thermometric scale a centigrade scale whose 100 degrees were defined by the expansion of hydrogen at an initial pressure of 1 m of mercury. Of course the boiling temperature of a liquid varies with pressure, so a standard atmospheric pressure was also defined: 760 mm of mercury of density 13.59593 under standard acceleration of gravity. Standard gravity was gravity at the BIPM (*Bureau international des poids et mesures*, or International Bureau of Weights and Measures) laboratory in Sèvres (just southwest of Paris) divided by 1.0003322 to relate it to 45° and sea level [1].

Not long after the meter was embodied by its international prototype, CIPM proposed (in 1891) to relate the meter to the wavelength of a well-defined light source

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as a way of tying it to an invariant of nature. BIPM recruited Albert Michelson (1852–1931) for the task, his work in interferometry being well known. He had written in 1889 on the possibility of using light as a length standard [2]. He recognized that most radiations, including those of sodium and mercury, were too complex to do the job; we would say that they were insufficiently monochromatic. In the process of his work at BIPM, Michelson and René Benoît measured the meter as 1,553,163.8 wavelengths of the red cadmium line. Charles Fabry, Alfred Perot and Benoît in 1906 arrived at a very similar value (1,553,164.13) but with an uncertainty about a factor of 10 smaller. The first formal proposals to redefine the meter in terms of wavelengths of light were discussed by the 7th CGPM in 1927, but no new definition was adopted until the 11th CGPM in 1960 [1].

Although it would be some time before the meter was redefined in terms of atomic constants, these efforts represent an attempt to return to the rationalist desire to base measures in invariable quantities. And they reflect an understanding that nature's invariants are to be found at the microscopic rather than the cosmic or planetary level. As James Clerk Maxwell (1831–1879) put it in 1870 [3]:

> If, then, we wish to obtain standards of length, time, and mass which shall be absolutely permanent, we must seek them not in the dimensions, or the motion, or the mass of our planet, but in the wave-length, the period of vibration, and the absolute mass of these imperishable and unalterable and perfectly similar molecules.

Around the turn of the century, three national metrology laboratories were founded that would collaborate over the next century and beyond in the international metrology regime. The first of these was the Physikalische-Technische Reichsanstalt, established in Berlin in 1887. The National Physical Laboratory near London and the National Bureau of Standards near Washington, DC, followed in 1900 and 1901 respectively. Also near the turn of the century, the 3rd CGPM adopted language to clarify that the kilogram was a unit of mass, not of weight. This had been understood for some time, but not explicitly stated [1].

The international metrology institutions extended their purview in the opening decades of the twentieth century. The 5th CGPM in 1913 endorsed a program to establish a thermodynamic (absolute) temperature scale. Its stated purpose in doing so was to meet a need in both theoretical and—given the fairly recent accessibility of very low temperatures—experimental physics. The CGPM called on the directors of national metrology laboratories to collaborate in planning and carrying out the necessary experiments. That cooperation did not get very far before the Great War broke out. The coordination that led to the extended temperature scale adopted by the 7th CGPM in 1927 set a precedent for metrological collaboration [1]. That cooperation included work on the explicit-constant SI (Sect. 5.3) and extends to the present.

At the next CGPM in 1921, expansion of BIPM activities to other units that required international standards was discussed. At signs of resistance from some, the extension was focused on electrical units. In the end, the CGPM resolved to have the CIPM coordinate experiments needed for electrical measurements and, after a future CGPM agreed unanimously to do so, the BIPM would conserve electrical standards. After work in the 1930s and the chaos of World War II, CIPM in 1946 resolved to bring absolute electrical units—ampere, volt, ohm, coulomb, farad, henry and weber—into effect as of 1 January 1948. It also adopted definitions of mechanical units of force, energy and power (named newton, joule and watt respectively) to which the absolute electrical units were referred. The ampere was the one electrical unit based entirely on mechanical quantities [1]:

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

The 10th CGPM in 1954 adopted a resolution to base an international system of units on the meter, kilogram, second, ampere, degree Kelvin and candela as units of length, mass, time, intensity of electrical current, thermodynamic temperature and luminous intensity. The CIPM established a commission to implement this decision to establish the system. The resolution that established the system in 1960 (at the 11th CGPM) was long and detailed. It included a name for the system (Système International d'Unités, abbreviated SI), the list of six base units, 27 derived units, and prefixes and abbreviations from tera- ($\mathrm{T} = \times\ 10^{12}$) to pico- ($\mathrm{p} = \times\ 10^{-12}$) [1].

When the SI was launched, the kilogram was the base unit of mass, defined by the international prototype kilogram of 1889. A proposal was made to change the name of kilogram since it was undesirable for one of the base units to have a prefix, but the name survived. The 1889 meter standard became, in effect, a museum piece, albeit still one conserved by the BIPM. The 10th CGPM in 1954 had approved in principle a move toward redefining the meter in terms of wavelengths of light, but it did not specify a definition. One of the questions left outstanding was which light to use, and a consultative committee in 1957 recommended a transition in krypton 86. The definition adopted by the 11th CGPM in 1960 was 1,650,763.73 times the wavelength of the transition in vacuum between the $2p_{10}$ and $5d_5$ energy levels of the atom of krypton 86 [4].[1]

4.2 The Quantity Time to the Establishment of the SI

At the launch of the SI, the second was selected as the base unit of time. Terry Quinn, director emeritus of BIPM and author of a very informative book on the history of the international metrology regime, writes "It is perhaps surprising to realize that until 1956, there was no official definition of the second. Everyone knew that it was simply the fraction 1/86,400 of a day and, of course, everyone knew what a day was" [1].

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[1] This publication of the BIPM is commonly known as the SI Brochure. The most recent editions of the brochure are available in both French and English. In addition to current definitions and specifications of the SI, the brochure contains an appendix of past decisions made by CGPM and CIPM affecting the units.

The nature and measurement of time are rich subjects about which much has been written. Readers interested in a brief introduction to the nature of time from the origins of human conceptions of time to temporal applications of relativity, and of the second law of thermodynamics, will find much to appreciate in G. J. Whitrow's *What is Time?*, even 50 years after its original publication [5]. A more detailed look at attempts to organize time, chiefly focusing on calendars, can be found in Duncan Steel's *Marking Time* [6].

In the latter book, among others, one can see an explanation of where the definition of the second and the origin of the word come from. Both minute and second refer to divisions of a larger unit, in this case of the hour. The minute is the first *small* division (Latin *pars minuta prima*) and the second is the *second* small division (*pars minuta secunda*).[2] Each of these divisions is 1/60 of the next larger unit. Sexagesimal divisions date back to the Babylonians [6].

But where did the hour come from? Surely it is not a natural measure? Steel dates the hour to about 2100 BCE in ancient Egypt. Then and for long afterward, it referred to a duodecimal division of the day or of the night. According to current concepts of duration, the hour did not then represent a constant duration. A daytime hour had a different duration than a nighttime hour, and the duration of each changed continuously over the year. Twice a year, at the equinoxes, the durations of the day and the night were equal, and so then were their divisions; only at the equinoxes was the day divided into 24 equal hours [6]. The Greek astronomer Hipparchus of Nicaea (c 190–120 BCE) proposed dividing the day into 24 equinoctial hours [7], but this was not widely done in Europe until the late thirteenth century CE, when weight-driven mechanical clocks could keep equal hours [8].

As Quinn noted, everyone knew what a day was, at least by 1956. Or at least there was an official definition before that time, for there are several different ways to reckon a day based on astronomical phenomena. The solar day is the interval between successive apparent transits of the sun over a particular meridian. The sidereal day is the interval between successive transits of a fixed star [6]. Many cultures measured the day as the interval between successive sunrises or sunsets. In 1884, the International Meridian Conference adopted a definition of a universal day as a mean solar day, from midnight to midnight, at the meridian through the Royal Observatory at Greenwich, England [9].

The second could be defined before it could be accurately measured. The earliest quotation in the *Oxford English Dictionary* for second as a measure of time is from 1588 in a statement giving the length of a year in days, hours, minutes and seconds [10]. At that time, the best mechanical clocks could gain or lose hundreds of seconds per day. An interesting graph in *What is Time?* illustrates the increase in precision in timekeeping from the middle thirteenth through the late twentieth centuries, listing a few of the technologies that enabled those increases. The first of those breakthrough technologies was the pendulum; improvements in pendulum clocks pushed precision from the seventeenth into the twentieth centuries. And, as seen in Chaps. 1 and 2,

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[2] In angular measures, minute and second have the same relationship to degree that they have to hour in temporal measures.

a pendulum that made one swing per second was seriously considered as a rational standard for length. The baton for precision was briefly passed to oscillations in piezoelectric quartz crystals. By the middle of the twentieth century, atomic clocks were the most precise timekeeping devices [5].

Such precise measurement of time allowed for the observation that the day was increasing in duration by about 1.7 ms per century and that year-to-year fluctuations could be of the same magnitude. Astronomers in the International Astronomical Union were looking for a more stable second from the 1950s. In 1956, CIPM adopted a definition of the second as 1/31,556,925.9747 of the duration of the tropical year 1900. Because this second was slightly smaller than the stated fraction of the then-current tropical year, "leap seconds" had to be periodically introduced—which causes headaches for satellite systems and other very high precision timekeeping [1]. This was the second that was adopted as the base unit of time in the SI.

4.3 Temperature to the Establishment of the SI

At the establishment of the SI, the base unit of thermodynamic temperature was the degree Kelvin, abbreviated °K. The absolute thermodynamic temperature scale was fixed by setting the temperature of the triple point of water[3] at 273.16 °K [4]. Hasok Chang's interesting and thought-provoking book *Inventing Temperature* examines in considerable historical and philosophical detail the difficulties in developing reliable and standardized devices for measuring temperature [11]. This section will rely extensively on Chang's account for a much-abbreviated sketch of key developments from the early days of thermometry to the definition of a thermodynamic temperature scale.

Defining a temperature scale by the freezing and boiling points of water and dividing this interval into 100 even portions was not a new idea when CIPM set up its temperature scale in 1887. (See Sect. 4.1) Taken for granted in this idea is the selection of fixed points on which to base such a scale. In the seventeenth and eighteenth centuries, the points on which to base a scale were by no means taken for granted. Even establishing the existence of fixed-temperature points was difficult in the absence of temperature scales based on fixed points. The freezing and boiling points of water emerged as widely but not universally recognized fixed points for thermometry by the middle of the eighteenth century. Even after that, questions remained about the fixity of the boiling point, involving complications such as the pressure-dependence of ebullition and the phenomenon of superheating [11].

Implicit in a two-point definition of a temperature scale is the measurement of a property of a material that changes continuously and monotonically between the

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[3] At the triple point of a pure substance, that substance can exist in solid, liquid and gaseous (vapor) forms simultaneously. (That is, the forms are in equilibrium: there is no tendency for one form to change to another.) A triple point occurs at a unique temperature and pressure. For water, the triple point occurs at a very slightly higher temperature than the standard freezing point (namely 0.010 °C) and a pressure only about 0.006 times that of the standard atmosphere.

two fixed points. For example, one can imagine a small reservoir of mercury in a bulb at the bottom of a narrow uniform closed tube. If one marks the position of the mercury in the tube at the freezing point of water and labels it 0 and then marks the position at its boiling point and labels it 100, one can divide the distance between the two marks into 100 equal portions, and the position of the mercury along that scale is the measure of the temperature. Unfortunately, if one does the same thing using alcohol as a working fluid, the two thermometers diverge by a few degrees. And if one attempts to do the same thing with water, the divergence is even greater.[4] (See Fig. 4.1) If temperature corresponds conceptually to a physical property (the degree of heat or cold) independent of the proxy by which it is measured (the expansion of a fluid), then which fluid—if any—best tracks temperature [11]? Edmond Halley (1656–1742) expressed his doubts in 1693: "… the same degree of Heat does not proportionally expand all Fluids … Thermometers graduated by equal Parts of the Expansion of any Fluid, are not sufficient Standards of Heat or Cold" [12]. By the middle of the nineteenth century, gases were generally accepted as the most reproducible thermometric fluids thanks largely to the extensive and meticulous experiments of Henri Victor Regnault (1810–1878) [11].

By 1850, temperature could be measured reliably, but the theoretical nature of temperature and its relation to heat remained unclear. For much of the seventeenth and eighteenth centuries, cold was entertained as a possible physical phenomenon in its own right. By the end of the eighteenth century, though, caloric theories of heat left no room for cold as anything other than absence of heat. By the middle of the nineteenth century, some versions of dynamical theories of heat proposed that temperature was proportional to the kinetic energy of the random motion of gas molecules. John James Waterston proposed such a connection in the 1840s in a paper that remained in the archives of the Royal Society unpublished until 1892. From about 1850 Rudolf Clausius (1822–1888) was the researcher who brought this notion of temperature to the attention of the larger scientific community. Meanwhile William Thomson (1824–1907, later made Lord Kelvin) had introduced a definition of temperature in terms of the theory of heat engines by Sadi Carnot (1796–1832). Thomson called this definition "absolute" meaning that it was independent of the properties of any particular material or working fluid. It was not absolute in the sense that it had a definite theoretical zero point; it did not. Thomson reconsidered his definition at the behest of James Prescott Joule (1818–1889) and in a paper co-authored with Joule formulated a definition whereby a ratio of temperatures was equated to a ratio of heat inputs and discharges of an ideal heat engine. This definition of temperature does have an absolute zero,[5] and it is also absolute in the sense of Thomson's previous definition. The problems of rigorously approximating this definition—deliberately independent of material properties and based on an idealized conceptual construct—in practical thermometry occupied physicists and metrologists into the twentieth century [11].

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[4] Water would make a terrible thermometric fluid because its density does not change monotonically over this range. As noted in Sect. 2.7, the density of water goes through a maximum value at 4 °C.

[5] The absolute zero of this scale is one previously identified by Guillaume Amontons (1663–1705) as the temperature at which the pressure of air would become zero based on extrapolation.

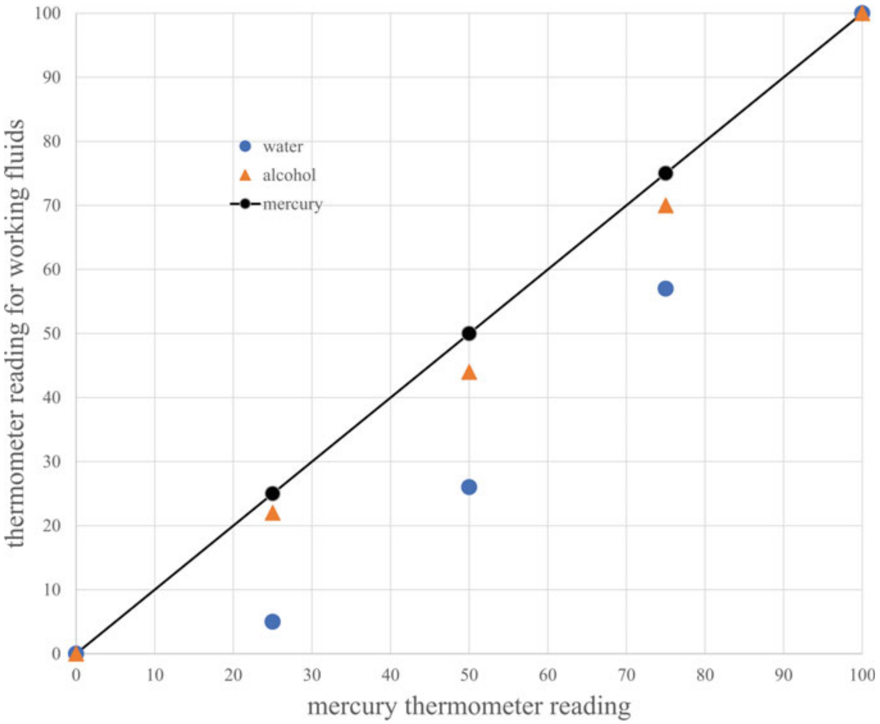

Fig. 4.1 Readings of thermometers based on various working fluids compared to the temperature read by a mercury thermometer (All three thermometers read 0 at the freezing point of water and 100 at the boiling point). Data given in Lamé 1836 [13]

Nevertheless, a temperature theoretically based on Thomson and Joule's definition in which the freezing and boiling points of water were 100 degrees apart was known as Thomson's absolute temperature scale later in the nineteenth century, and still later (after Thomson was made Baron Kelvin) as Kelvin's scale or the Kelvin scale.

The temperature scale adopted by CIPM in 1887 and expanded by the 7th CGPM in 1927 was a practical one, not a thermodynamic one [1]. At the 9th CGPM in 1948, the triple point of water was recognized as the single fixed point[6] on which an absolute thermodynamic scale would be established before long. (A temperature scale with zero at absolute zero requires only one non-zero fixed point.) At the same time, the CGPM adopted "degree Celsius" (°C) as its preferred unit name for conventional temperature, and it listed "degree absolute (°K)" as its unit for absolute thermodynamic temperature. The next CGPM set the triple point of water at exactly 273.16 °K, a choice which made the numerical value of temperature *differences* measured on the Celsius and Kelvin scales equal [4].

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[6] The triple point is a more natural and less arbitrary fixed point than a standard freezing or boiling point. The latter are defined for a standard (and therefore somewhat arbitrary) pressure.

4.4 Electrical Units to the Establishment of the SI

The ampere (A), a unit of electrical current, was the electrical unit selected to be a base unit in the SI [4]. Electrical units were not part of the Metre Convention, and they did not enter the purview of the CIPM for several decades. They had, however, been the subject of formal discussions to establish definitions and standards in national and then international venues for decades before CIPM took them up.

The British Association for the Advancement of Science (informally known as the BA) appointed a committee to look into standards for electrical resistance at its 1861 meeting [14]. Thomson, whose important work in temperature and thermodynamics was glimpsed in the previous section, was influential in having the committee established [15]. The committee moved beyond standards of resistance, seeing a need for a coherent system of electrical units. Although the committee was not international in membership, they were cosmopolitan in outlook, advocating the definition of electrical units based on the "French metrical system" rather than the units in common use in Britain and soliciting opinions from scientists throughout Europe and the US [16].

At the same BA meeting that established a committee on electrical standards, a presentation by two engineers on the Atlantic Submarine Telegraph project, Latimer Clark and Sir Charles Bright, proposed a set of practical electrical units, not connected to mechanical units. They argue "The science of Electricity and the art of Telegraphy have both now arrived at a stage of progress at which it is necessary that universally received standards of electrical quantities and resistances should be adopted." Their proposal used the names of important researchers in electricity as the basis for names of their units. For example, they proposed the name Ohma for the electromotive force produced by a Daniell cell, Farad for a charge induced by 1 Ohma across plates of area 1 m^2 separated by 1 mm of dry air, and Galvat for a current of 1 Farad per second [17]. Clark and Bright appear to have initiated the practice of naming scientific units after prominent scientists, a practice followed by later committees charged with describing electrical units [18].

The time seemed ripe for standardization of electrical units. Practical applications of electricity and magnetism, such as the transatlantic telegraph cable, were being deployed. Moreover, several different conventions for electrical and magnetic units were in circulation, none of them really having convenient magnitudes for practical applications.

Two main links of electrical and magnetic phenomena to mechanical force led to different units (with different physical dimensions) for the same quantities. "Electrostatic" units regard as fundamental the electrostatic force law of Coulomb (mentioned in Chap. 2 for serving on committees devising the metric system). Force has dimensions of $M\,L\,T^{-2}$, where M represents the dimension mass, L length, and T time. In electrostatic units, the dimensions of electrical current are $L^{3/2}\,M^{1/2}\,T^{-2}$. (For more detail, see Ref. [18], particularly the appendix.) "Electromagnetic" units, on the other hand, use the electromagnetic force law of André-Marie Ampère (1775–1836) as the fundamental link to mechanical quantities. An electromagnetic unit of electrical current has dimensions $L^{1/2}$ $M^{1/2}$ T^{-1}. Either choice is legitimate; whichever force law is taken to be fundamental amounts to introducing a proportionality constant into the other force law. Either choice leads to systems of electrical and magnetic units that are absolute in that they are tied to already existing mechanical units.

Therein lies another choice, namely of mechanical units (mass, length and time). The system favored in Britain for scientific work at this time and eventually adopted more widely was the cgs system, in which lengths are specified in centimeters, masses in grams, and time in seconds. The cgs electrostatic unit of current is 1 $\mathrm{cm}^{3/2}$ $\mathrm{g}^{1/2}$ s^{-2}. In Germany, the preferred set of mechanical base units was the millimeter, milligram, and second [19]; call it mms. Under this system, the electrostatic unit of current is 1 $\mathrm{mm}^{3/2}$ $\mathrm{mg}^{1/2}$ s^{-2}. Electrostatic units have the same dimensions but different magnitudes in the cgs and mms systems, and they are different than electromagnetic units for the same physical quantity [18].

Laboratory and commercial measurements of electrical and magnetic phenomena typically differed by many orders of magnitude from the systems of units sketched above. A desire for units comparable in magnitude to typical measurements was natural. Such units were described as “practical.” At least at first, some practical units were proposed in terms of absolute ones (such as the ohm proposed to be 10^{10} electromagnetic mms units of resistance) or they could be based on arbitrary standards (such as a column of mercury of specified dimensions proposed as a unit of resistance). But later in the nineteenth century, “absolute” was often used in a more restrictive sense, applied only to units whose relationship to other units in the system had a numerical factor of 1 [18].

In 1865, the BA Committee specified a practical standard of electrical resistance, which became the first of yet another set of electrical and magnetic units, eventually to be known widely as the BA system or the practical system. The committee chose the resistance unit to be 10^{10} mm s^{-1} (that is 10^{10} electromagnetic mms units of resistance) because it wanted a decimal multiple of a unit already in use and because a physical standard of approximately this magnitude had already been developed and found convenient [18].

Members of the Committee discussed ideas for names of units as well as for ways of indicating decimal multiples and divisions. They were aware that if a coherent system was to be developed, at least some of its units would be of inconvenient magnitude for at least some practical uses [18]. One of the committee members, C. F. Varley, wrote to Thomson in 1865 describing names he had discussed with Clark and Fleeming Jenkin. Clark had proposed the names Galvad for potential, Ohmad for resistance, Voltad for current, and Farad for charge. The names for one million units would be Galvon, Ohmon, Volton, and Faron respectively, in effect representing a factor of one million by the suffix -on. (Recall that at this time, the prefixes of the metric system only ranged from 10^{-3} (milli-) to 10^{4} (myria-). Jenkin replied that using an ending to denote magnitude would be confusing, especially in cases of sloppy handwriting [20]. In 1872, after the committee on resistance standards had expired, the BA appointed another committee, this one “for reporting on the Nomenclature of Dynamical and Electrical Units” [21]. The following year, that committee endorsed the prefixes mega - ($= \times 10^{6}$) and micro - ($= \times 10^{-6}$), which were apparently already widely used in practice. For still larger decimal multiples they suggested appending the cardinal number of the appropriate power of ten to the name of a unit (for example, centimeter-nine = 10^9 cm) and for smaller divisions prefixing the ordinal number of the absolute value of the relevant power of ten to the name of a unit (for example, ninth-second = 10^{-9} s). This report also gives the names and values of practical units of resistance, electrical tension (potential) and capacitance [22]. The ohm was the BA unit of resistance introduced in 1865, equal to 10^9 electromagnetic cgs units. The volt (10^8 electromagnetic cgs units) and farad (10^{-9} electromagnetic cgs units) had never been formally endorsed but were in use [23].

International expositions were the occasion for conferences and discussions of electrical units in the late nineteenth and early twentieth centuries. The first International Electrical Congress was held in Paris in 1881 along with an international electrical exposition. For the most part, the nations sending representatives were the same ones who attended the 1875 metric conference (Sect. 3.3, Table 3.1) along with Japan and most of the nations of Central America. Among the actions taken was the adoption of a set of practical electrical units. The Congress's commission on electrical units passed seven resolutions, including: to use cgs mechanical units as the foundation for electrical units; to retain the practical units ohm and volt with their definitions then in use; to define the current resulting from one volt of potential through one ohm of resistance as an ampere; to call the charge transferred by an ampere current in one second a coulomb; and to define a farad as the capacitance that produces a volt of potential difference when it stores a coulomb of charge [19]. Practical units of work and of power were adopted at the International Electrical Congress of 1889 in Paris. These units were 10^7 times the corresponding cgs units, and they were named joule for work and watt for power [24].

The International Electrical Congress of 1893, held in Chicago in conjunction with its Columbian Exposition, endorsed an "international" system of electrical and magnetic units based on cgs electromagnetic units but defined in terms of practical standards [25]. (This situation was somewhat analogous to the meter which was based on 1/10,000,000 of the length of a quarter meridian but whose official definition at the time was a platinum-iridium bar at the BIPM.)

The delegates to the International Electrical Congress in St. Louis, Missouri, in 1904 adopted a resolution to establish an international commission on standardization and nomenclature for electrical apparatus. The International Electrotechnical Commission (IEC), still in existence today, was set up in 1906. Lord Kelvin was its first president [26].

A proposal by Italian physicist Giovanni Giorgi (1871–1950) for an extension of the metric system to include electrical units made its international debut among the papers presented at the same Congress. Giorgi noted that the practical units of work and power, the joule and the watt, would be the units of work and power respectively in a system that treated the meter, kilogram and second as base units (an MKS system of units). If one further selected one of the practical electrical units as a fourth base unit, then the other practical electrical units (which already formed a coherent system of electrical units) would be part of the new coherent system. In this new system, neither Coulomb's nor Ampère's force law would be privileged; both would require proportionality constants. Giorgi proposed the ohm as the electrical base unit [27].

Giorgi's proposal was not adopted by any official body until the IEC endorsed the MKS system in 1935; it left the selection of the electrical base unit temporarily unspecified [28]. The CGPM and the IEC seemed to be moving in opposite directions in the 1920s and 1930s. Having taken electrical matters under its consideration in 1921, the CGPM set up a Consultative Committee for Electricity in 1927. In 1933 the 8th CGPM endorsed absolute electrical units for future metrological work; in effect, this preferred cgs units to the practical international units [29]. Soon after the end of World War II, though, the absolute electrical and magnetic units established by CIPM (Sect. 4.1 above) were essentially the international practical units defined in a way that depended on MKS mechanical units [4].

4.5 Luminous Intensity to the Establishment of the SI

At the launch of the SI, the candela (cd) was included as a base unit of the quantity luminous intensity. The definition of the candela at that time was the luminous intensity of a blackbody radiator of area 1/60 cm^2 at the melting temperature of platinum [4]. A very brief sketch of international units for photometry up to that time follows.

First some terminology is in order. Luminous intensity is a measure of visible light, that is, of electromagnetic radiation capable of detection by human vision. Photometry deals with the measurement of visible light, whereas radiometry measures electromagnetic radiation (usually in terms of energy) regardless of its visibility. Thus photometry is a matter of both physics and physiology [30]. The spectral range of visible light is not precisely limited, even by such standards organizations as the CIE (Commission internationale de l'éclairage or International Commission on Illumination). The lower wavelength limit is in the range of 360–400 nm and the upper 760–830 nm [31].

Specific light sources were used as standards for luminous quantities. For example, in Victorian England, the standard candle was made of 2 troy ounces of spermaceti wax burning at a rate of 120 grains per hour [30]. An "international candle" was defined in 1909 by agreement of standards laboratories of the UK, France, Germany and the US. This cooperative venture grew out of a proposal made by Thomas Vautier, President of the French Technical Society of the Gas Industries, at an International Congress on Gas held in conjunction with the Paris Exposition of 1900. A few years later (1913), international cooperation on photometry was formalized by creation of the CIE. Unlike CIPM, CIE was not an intergovernmental body, but because it was comprised of representatives from lighting industries around the world it was influential in lighting practices [1].

The CIPM's Consultative Committee for Electricity added photometry to its portfolio in 1929. The 8th CGPM in 1933 established a separate Consultative Committee for Photometry. Late in the 1930s that committee recommended defining a photometry standard based on radiation of an ideal blackbody. In 1946 CIPM adopted a unit of luminous intensity based on blackbody radiation at the melting point of platinum. It called the unit the "new candle." The next CGPM (the 9th in 1948) changed the name of the unit to candela [1].

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