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Carmen J. Giunta

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From Revolutionary France to the Constant-Based SI

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Preface

The history of units has been an interest of mine for many years, albeit one I have pursued less than systematically. Units and constants named after prominent scientists I have found particularly interesting. The opportunity to delve into the details of history that brought the metric system into existence in revolutionary France and that transformed it from a national system little used even in its country of origin into a system curated by an international body and used literally all over the world was very attractive to me, and it is a pleasure to summarize what I found out in the following pages.

Perhaps a word of justification is in order about why a series dedicated to the history of chemistry is publishing a book that arguably is more appropriate to the history of physics. I do not dispute the claims of physics to the metric system or the SI; however, that claim is not exclusive. Teachers and students of chemistry make extensive use of a broad range of units from the International System of Units (Système International d'Unités or SI). Even the most basic operations in a chemical laboratory include collecting liquids in milliliters, weighing out solid reagents in grams and reporting temperatures in degrees Celsius. As a long-time instructor in physical chemistry, I can report that the only SI base unit that failed to enter my course is the candela. Of course there is one base unit peculiar to chemistry, the mole, to which this book pays particular attention.

The heart of the book, though, is the development of the metric system in revolutionary France, tracing the evolution of proposals put before the government from the first proposals to the National Assembly in 1790 through the fabrication and deposit of definitive standards in 1799. No attempt is made to survey the variety of units in use before the development of this system in either France or elsewhere; however, an introductory chapter introducing some of the ideas about decimal and rational measurements developed before the invention of the metric system will precede consideration of revolutionary France.

Chapter 2 treats the sequence of events that led to the formulation of the system—the twists and turns in proposals and protagonists during the revolutionary and republican years. The republican calendar and republican day are also described in this chapter, but more general considerations of time will come later.

A discussion of metrication (adoption of the metric system) inside and outside France follows in Chap. 3. In France, the system was set aside even before the restoration of the monarchy, and it was not in universal use even there before 1840. Before the end of the nineteenth century, though, an international treaty had been signed by most of the nations of Europe and the Americas establishing international bodies to maintain and disseminate the metric system.

These bodies gradually turned their attention to measures outside the scope of traditional weights and measures (i.e., beyond length, area, volume and mass), eventually establishing a more comprehensive system of units, the SI in 1960. At this point, measures of time, temperature, electrical quantities and light are taken up briefly.

Modifications of SI after its launch are the subject of Chap. 5. The addition of the mole to the list of base units is of particular relevance for chemistry, so the history of the mole, amount of substance, Avogadro's number and the Avogadro constant are described. The revision of the SI to its current explicit-constant formulation concludes the chapter.

Efforts of reform of weights and measures in the USA, which remains the most populous and one of the very few nations on earth where metric weights and measures are not used exclusively, are the subject of the final chapter.

Syracuse, USA Carmen J. Giunta

Acknowledgments

I thank two bodies of the American Chemical Society (ACS) for allowing me to pursue my interest in the history of units: the Division of the History of Chemistry and the Committee on Nomenclature, Terminology and Symbols. The former has let me organize a symposium on names of units, and the latter helped me think about implications for chemistry and chemical education of the recent revision of the SI while that revision was in process. Thanks to Gregory Girolami and Vera Mainz for access to their collection of documents on the early metric system and for stimulating conversations on the subject. Thanks also to Series Editor Seth Rasmussen for encouraging me to harness that interest to produce this volume.

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About the Author

Carmen J. Giunta is Professor of chemistry emeritus at Le Moyne College in Syracuse, New York, where he taught from 1990 through 2019. He is a physical chemist by training, having earned a Ph.D. in Chemical Physics from Harvard in 1989 working with Roy G. Gordon. He has been active in the ACS Division of the History of Chemistry since the late 1990s. He is editor of the Division's journal, the *Bulletin for the History of Chemistry*.

His interest in units and their history led him to serve for a decade on the ACS Committee on Nomenclature, Terminology, and Symbols. During that time, he organized a symposium on the history of units (2011 ACS Spring National Meeting) and published papers in the *Journal of Chemical Education* on the mole and the redefined International System (SI) of units and in *Substantia* on names of units. He is Co-editor with Vera V. Mainz and Gregory S. Girolami, of *150 Years of the Periodic Table: A Commemorative Symposium* (2021) in Springer's Perspectives on the History of Chemistry series.

Chapter 1
Introduction: Decimal Ideas Before Revolutionary France

Abstract The conceptual prehistory of the metric system is reviewed. The metric system, an artificial system of measures, did not evolve from customary measures previously in use in late eighteenth-century France, but from a set of ideas published by natural philosophers in the second half of the seventeenth century. These ideas included the utility of decimal arithmetic and a relatively few choices for a length standard derived from nature. Principles for new measures designed on philosophical principles were taken up by governmental bodies in Great Britain and the United States late in the eighteenth century, but no new measures emerged from those discussions.

1.1 Introduction

Weights and measures have a long history in human societies, one whose organic origins can be seen in the names of many units mirroring everyday objects. Examples include grains as units of weight and (human) feet or paces as units of length. Measures were tied to particular practices and commodities, for example land area to a day's harvest or planting, lengths for cloth to the width of local looms [1]. The story of customary units is not the story of this book, though. Readers interested in an account of measures and the premodern European societies that used them are referred to Witold Kula's classic *Measures and Men* [2].

The system of weights and measures that concerns us here is an artificial one, deliberately designed in a specific time and place and modified and augmented since that time. That system, commonly known as the metric system and later expanded to the International System of Units (Système international d'unités, or SI) was devised and implemented in the first French Republic during the final years of the eighteenth century.

The metric system did not "evolve" from the customary weights and measures in use in late eighteenth-century France, but neither did it spring fully formed from the enlightened minds of that nation's savants. The conditions and people that produced the metric system in revolutionary and republican France will be taken up in detail in the next chapter. This chapter briefly summarizes the intellectual prehistory of

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artificial, rational measurements—of ideas that could be implemented, with some modification, if political conditions permitted.

1.2 Simon Stevin and Decimal Arithmetic

In the twenty-first century even schoolchildren are so accustomed to decimal notation and arithmetic that it is difficult to imagine reckoning without them. But writing fractions as sums of tenths, hundredths, etc., was not a "natural" extension of writing whole numbers as sums of units, tens, hundreds, etc. The advantages of decimal arithmetic were first proposed and explained to Western Europeans in 1585 by Simon Stevin (1548–1620) in a short book called *De Thiende* [3] in Flemish (Stevin's mother tongue) and *La Disme* in French [4].

Stevin was born in Bruges (in present-day Belgium) and spent much of his career in what is now the Netherlands, including Leiden and Delft. He was a polymath, writing extensively on mathematical subjects but also in statics, hydrostatics, and earth science. George Sarton, a leading historian of science in the first half of the twentieth century, calls Stevin "perhaps the most original man of science of the second half of the sixteenth century" [5]. Although Stevin has been the subject of dissertations and monographs since Sarton's work, his work is not widely known outside specialist circles.

What makes decimal arithmetic so convenient is that its operations are like those of whole numbers. In effect, decimal arithmetic makes use of the positional representation of numbers introduced with the advent of zero and "Arabic" numerals. Positional numbers developed in India and were transmitted to Europe by Islamic scholars starting in the Middle Ages, although Roman numerals persisted in some places into the early sixteenth century. Stevin's notation was not quite ours. For example, he did not employ a decimal point or equivalent; rather, the fractional part of a number was marked by a circled 0, 1, 2, 3, etc., for ones, tenths, hundredths, thousandths, etc. [4]. See Fig. 1.1.

Despite the rather cumbersome notation, Sarton credits Stevin with explaining the idea of decimal arithmetic in full. Sarton mentions two other scholars working earlier in the sixteenth century as having used something like decimal fractions, including a separator between the whole and fractional parts of numbers, but without the understanding or justification set forth by Stevin. These were Christoff Rudolff in Augsburg (in present-day Germany) and Elijah Ben Abraham Mizraḥi in Constantinople (now Istanbul, Turkey). Sarton notes that the work of these scholars in widely separated parts of Europe suggests that the concept was maturing at the time. But he does not credit them as inventors of decimal arithmetic, employing what I think is a rather high bar that sounds to me more like completing an invention: "It is not enough to stumble on something; the inventor cannot be recognized as such until he has justified his invention and proved his full understanding of it and of at least some of its implications" [4]. Among the implications that Stevin illustrates in the appendix of

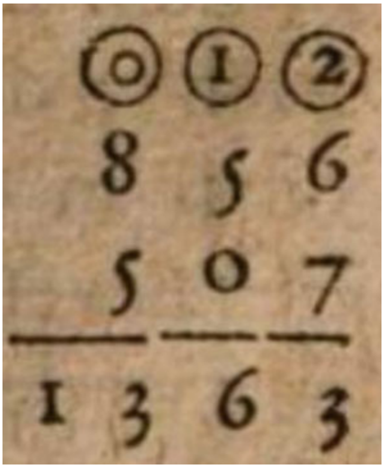

Fig. 1.1 Example of an addition from Stevin's *De Thiende* [3], courtesy Google Books. Current notation would render the addends as 8.56 and 5.07 and the sum as 13.63

his book is that decimal arithmetic can simplify calculations involving measures and currency.[1]

1.3 Early Examples of Practical Decimal Measures

An example of weights organized on a decimal system was described in Ciriacus Schreittmann's *Probierbüchlin* published in 1578. All that is known about Schreittmann is that he was an assayer in Weissenburg in the Bavaria region of Germany. The book's preface says that the manuscript had been kept among papers for more than 20 years before publication [6].

Assayers had to weigh small quantities of ore or refined metals, and they typically did so using a scaled miniature set of weights that were a fraction of the standard legal weights of the time and place, and in the same ratio as the legal weights. Assayers typically made their own. What Schreittmann described was how to make a set of miniature weights related amongst themselves by decimal multiples, which could then be compared to the relevant legal weights. The weights were built up from tiny pieces slightly too light to be measured on the assayer's balance. The next larger size in the set was made to balance 10 of the original size; the next larger size balanced 10 of that size; and so on. The largest weight in the set had a weight 4,000,000 times the lightest. (Note that since the lightest unit is the "base unit" of this decimal system, only multiples and no fractions were required.) It is apparent from the text that Schreittmann carried out the operations he describes [6].

[1] Currency was often discussed along with weights and measures in both theoretical and practical proposals for reform. This book will occasionally mention currency, but not enter into any detail on the subject.

Using traditional assayer's miniature weights to obtain a measure in legal units would entail obtaining a weight in the miniature units (for example, miniature pounds, ounces, drams, etc.), then dividing the result by the conversion factor between the miniature and legal weights, and reapportioning the result among the units of the legal system (e.g., legal pounds, ounces, drams, etc.). Carrying out the same measurement using Schreittmann's system would entail obtaining one weight as a large number of his tiny arbitrary units, dividing that single number by the appropriate conversion factor to the smallest legal unit—and then reapportioning the result among the legal units. Apparently Schreittmann's system of arbitrary decimal assayer's weights was not widely adopted [6].

Sarton comments that decimal metrology was slower in gaining acceptance than was decimal arithmetic. Still, he reports examples of decimally divided measuring sticks being sold in London as early as 1619 [4].

1.4 Theoretical Ideas About Universal Measures

The topic of universal measures was discussed quite early in the history of the Royal Society of London. The handwritten first Journal Book of the Royal Society records that Dr. Wilkins (John Wilkins, 1614–1672) read a paper about a natural standard at the meeting of 20 November 1661. Just a few months later, at the meeting of 5 February 1661/2, the Journal Book notes "Dr Wren [Christopher Wren, 1632–1723] intreated to think of an easy way for an universall measure other than a Pendulum" [7].

The basic idea was to adopt the length of a pendulum that beat exactly one second per swing as a length standard. A pendulum of that length is called a *seconds pendulum.* This name may give a mistaken impression that seconds could be measured so precisely at this time to make such a determination feasible based on individual swings. A better idea of the precision of time measurement of that era might be given by noting that many of the relevant texts describe a pendulum that made 3600 swings in an hour.

Natural philosophers throughout Western Europe determined the length of seconds pendulums and discussed their potential as the basis of universal measures repeatedly from the middle of the seventeenth century onward. Among the earliest such determinations—predating documented discussions of universal measures—were those by Marin Mersenne and Giovanni Battista Riccioli. Mersenne [8], a French savant whose name is still attached to a class of prime numbers, reported its length as 3½ feet. Riccioli [9], an Italian Jesuit astronomer specified 3 ancient Roman feet [10] and 4 inches.[2]

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[2] A footnote on feet is in order here. "Foot" and its equivalent in other languages is the name of an anthropometric length unit dating back to antiquity. As the name suggests, it is a length close to that of a human foot. The length was standardized in different times and different places to slightly different lengths [2]. Just how long the foot unit Riccioli used compared to the one Mersenne used would be difficult to determine. Estimates of the ancient Roman foot made in the twentieth century

In 1668, Wilkins set forth his ideas on measures in a relatively small portion of a much wider-ranging treatise, *An Essay Towards a Real Character: And a Philosophical Language* [11]. Wilkins was in search of universality in more than measure, as his title suggests. He considers several candidates for a universal standard based on natural phenomena. He raises the possibility of "subdividing a *Degree upon the Earth*," that is, of surveying a degree of latitude and taking a set fraction of it as a length standard, but rejects it as too difficult to be practical. But he considers a pendulum that beats a specified time to be the most likely realizable length standard. He attributes the idea to Wren, who is best known today as the architect of St. Paul's and other London landmarks built after the great fire of 1666. Wilkins proposes the length of the seconds pendulum, determined by Royal Society President Lord Viscount Brouncker and Christiaan Huygens (1629–1695), as the length standard. (Huygens, one of the foremost natural philosophers of his age, had invented the pendulum clock in the 1650s.) Wilkins suggests several length units based on decimal multiples or divisions of the standard, such as foot (1/10 of the standard), inch (1/10 foot), pearch (10 standard lengths) and furlong (10 pearches). Moving beyond length, Wilkins proposes that units of capacity—we would say volume—be related to the length standard, proposing to call the cube of the length standard a bushel and to define other units of capacity as decimal divisions of it. Weight units would be defined as the weight of capacity units of distilled rainwater. Wilkins also proposed decimal money based on measures of pure gold and silver [11].

Thus Wilkins's brief chapter on measures includes three key aspects of the rational systems of weights and measures proposed more than a century later in the design of the metric system and in discussions of weights and measures in the infant United States:

- a standard based on nature and believed to be invariable
- decimal multiples and divisions
- an integrated system, i.e., rational relationships among units of weight, capacity and length.

A less rational aspect of Wilkins's proposal that would also reappear in the late eighteenth and early nineteenth centuries is what seems to me the obviously confusing suggestion to give old names to new units [11].

Gabriel Mouton (1618–1694) of Lyon, France, is often credited with being the first to propose a universal length standard based on the size of the earth [4], although as we have seen in examining Wilkins's ideas, he was not the first to imagine such a basis. Mouton published his ideas near the end of a 1670 book mainly concerned with observations of the diameter of the sun and the moon. He proposed to define a *milliare* as the distance on the surface of the earth corresponding to one minute of arc of a great circle. Mouton's milliare was to be dived decimally into centuria, decuria, virga, virgula, decima, centesima and millesima, each unit defined as 1/10 of the preceding one. Note an attempt at some systematic nomenclature in the French roots

vary from about 29.6 to 31.6 cm [10]. The lengths quoted here for the seconds pendulum are to give a rough idea of its length as determined before there were accurate length standards.

for thousand, hundred, ten, tenth, hundredth and thousandth among the proposed names—an attempt marred by the presence of two units (virga and virgula) between the multiples and the fractions.

Meanwhile in 1671 Jean Picard (1620–1682) raised the possibility that the seconds pendulum might not have the same length everywhere on earth, even as he advocated a universal length standard based on it. He wrote of measurements reported from various places in Europe suggesting that the length of the seconds pendulum might be shorter the closer one approached to the equator. If that length was variable with location, then it could not serve as a universal measure—although it could still serve as a reproducible local standard [12]. Picard was an astronomer and member of the new French Académie des sciences (not yet the Académie royale). That same year the Académie authorized an expedition to Cayenne (now part of French Guiana in South America at 4°56′ North latitude) to make several kinds of scientific observations near the equator. Jean Richer, a French astronomer on the expedition, reported a small but reproducible difference in the length of the seconds pendulum, finding it about 3 parts per 1000 shorter in Cayenne than in Paris. After another 15 years or so, the variability of the seconds pendulum with latitude was generally accepted [4].[3]

Sarton writes that "as soon as it was realized that the seconds pendulum was not invariable it lost its value as a universal standard of length" [4]. It may be logically true, as Picard wrote at the time [12], that the seconds pendulum could not provide a universal length standard. Nevertheless, as we shall see, the seconds pendulum would be the basis of measures proposed with aspirations of universality a century later.

It ought to be emphasized at this point that all of the proposals for and discussions of universal measures outlined in this section were made by natural philosophers communicating primarily with each other and not in any advisory capacity to the officials who had charge of weights and measures. Furthermore, no international organization of savants took up these matters, even though some new national academies did so and many individuals corresponded with colleagues outside their national borders. Twenty-first-century readers would do well to remember that there were no international scientific institutions at the time such as IUPAC (the International Union of Pure and Applied Chemistry), let alone ones established by treaty, such as the BIPM (Bureau International des Poids et Mesures, in English the International Bureau of Weights and Measures; see Sect. 3.3).

The diversity of units of measure employed in different nations was an annoyance if not an obstacle in the international diffusion of science. In 1783, Scots inventor and natural philosopher James Watt (1736–1819) complained to Irish chemist Richard

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[3] This variation with latitude is due primarily to the fact that the shape of the earth is not quite spherical. Ignoring surface features, earth is an ellipsoid slightly flattened at the poles and slightly bulging at the equator. The distance from the center of the earth to sea level at the equator is about 0.3% greater than the corresponding distance to the poles. This makes acceleration due to gravity about 1% less at the equator than at the poles. That variation would make a seconds pendulum at the equator about 1% shorter than at the poles—if the earth were not rotating. The centrifugal force due to the earth's rotation opposes the force of gravity at the equator but is perpendicular to it at the poles; this reduces the length of the seconds pendulum at the equator by an additional 0.3%.

Kirwan (1733–1812) of the difficulties in translating units when trying to compare reports of chemical experiments by French scientists to Kirwan's; and it is even worse for experiments from Germany[4] because of the great variety of units employed there. Watt sketched an idea to Kirwan that he thought "may be accomplished if you, Dr. Priestley [Joseph Priestley, 1733–1804, best known today for his chemical discoveries], and a few of the French experimenters will agree to it." The idea was to establish decimally divided weights and measures, a "philosophical" pound and foot, preferably tied to a standard such as a pendulum of specified period. Watt was not particularly committed to any particular value for these units. And if the natural philosophers could not agree on units, decimal divisions alone would simplify conversions [13]. In the absence of international institutions or political sponsorship, it is no wonder that neither Watt's idea nor those taken up a century earlier came to fruition.

The utility of decimal divisions in weights and measures was also given a mention in one of the quintessential publications of the Enlightenment, the *Encyclopédie* of Diderot and D'Alembert. The article on decimal arithmetic, written by D'Alembert, concludes with the assertion that decimal divisions would be very desirable in the pound, the penny, the toise (roughly a fathom), the day and the hour [14].

1.5 Weights and Measures in the British Parliament

The final two sections of this chapter describe actions contemporary with the metric reforms of the French Revolution—at least with their beginning. I include discussions of weights and measures in eighteenth-century Great Britain (here) and (in Sect. 1.6) the United States in this chapter rather than in the next for two reasons. First, the invention of the metric system in republican France deserves a chapter of its own. Second the discussions in the two anglophone nations had little or no influence on the developments in France, so the stories can be told largely separately. We will see the ideas developed in the previous section forming the basis of discussions in Great Britain, the US and France not just among natural philosophers but in governmental bodies.

John Riggs Miller (c. 1744–1798), baronet and Member of Parliament for Newport, Cornwall, made the first of three speeches on reform of weights and measures in the British House of Commons in July 1789 [15]. I do not know why Miller took up the issue in Great Britain at this time. His arguments for uniform weights and measures are similar to those heard at the same time in France but without revolutionary urgency: that different measures in different towns and for different goods are an obstacle to trade and a temptation to unfair dealing. These observations were certainly valid, but they were perennially valid, not particular to

[4] Germany was Watt's word. Although not a nation-state at that time, Germany was a distinct region within Europe, albeit one with fuzzy borders.

the late eighteenth century. Moreover, Miller asserts, uniform weights and measures are part of a distant past ideal of good governance, the Magna Charta [15].

Miller's first speech simply announces his interest in bringing the topic of uniformity of weights and measures before the Parliament. His second speech (in February 1790) calls for collecting local standards from throughout the nation to assess the extent to which measures were in disarray before proposing a new system on philosophical principles. He outlines those principles in his third speech, in April 1790. By this time the topic of reform of measures had been introduced in the French National Assembly and Miller was aware of what had been proposed there. But he says that he had already formulated the principles he presents in his speech. Miller's outline shares the characteristics of philosophical proposals described above: based on an invariable natural standard and employing decimal multiples and divisions. In his April 1790 speech, Miller's preferred length standard was a pendulum beating seconds at London [15].

Both the high point and the end of this period of interest in reform of weights and measures in Great Britain occurred in 1790. Miller had his speeches published along with the proposal Talleyrand made in 1790 to the French National Assembly (described in the next chapter) and some other material. Both the French proposal and the one Miller published after his third Parliamentary speech raised the possibility of cooperation between Great Britain and France in reforming measures. Miller's published proposal suggests the average of seconds pendulums at the equator and the pole as a length standard [15]. Meanwhile, another book on reforming weights and measures on philosophical principles appeared in Britain. Sir James Steuart published a plan contained in papers drawn up by his late father, also Sir James Steuart (1712–1780), a distinguished political economist. The elder Steuart also advocated a decimal system based on a seconds pendulum length standard [16]. But by the middle of the year, an official proposal for cooperation on weights and measures made by the French ambassador was rebuffed by the British foreign secretary. After Parliament was dissolved in 1790, Miller was not re-elected [17]. When the United Kingdom next seriously considered uniform weights and measures in the 1820s, cooperation with France would not be on the agenda.

1.6 New Measures for the New United States?

Uniform weights and measures were a natural topic for a new confederation of independent states, an opportunity to set standards to which the disparate parts might adhere. The Articles of Confederation, adopted in 1777, gave the united states, in congress assembled, the right to fix weights and measures throughout the country [18], a right not taken. The US Constitution, drafted in 1787 and effective in 1789, gives a similar right to the Congress (Art. I, Sect. 8) [19]. In January 1790, President George Washington (1732–1799) raised the issue in his first annual address to Congress. Currency, weights and measures were not the focus of the brief speech, but they appear in the middle of a short list of agenda priorities: "Uniformity in the

Currency, Weights and Measures of the United States is an object of great importance, and will, I am persuaded, be duly attended to" [20]. A week after Washington's speech, the House of Representatives assigned the task of preparing a plan or plans for uniformity in weights, measures and currency to the Secretary of State, Thomas Jefferson (1743–1826).

Before Jefferson even received his commission, a William Waring of Philadelphia had submitted to Congress a plan for the regulation of weights and measures [21]. Waring was a teacher at the Friends' Latin School of Philadelphia around this time, and a co-author of the *American Tutor's Assistant*, a book of "practical arithmetic." Waring proposed a length standard of a seconds pendulum at the equator. He proposed a decimal system retaining the names of a few measures in current use for units of similar size, but mainly introducing new names for new units. His system would ideally have a weight standard based on a fixed volume of water; however, he had a backup system for using the avoirdupois pound already in use. But whatever the weight unit, it would be divided decimally.

Jefferson's report to the House [22] is dated 4 July 1790. It begins by reviewing considerations involved in selecting an invariable length standard. He proposes a uniform cylindrical rod of iron that beats seconds at 45° latitude and sea level, kept in a cellar or some other place where temperature variations are minimal. The cylindrical rod is a variation on the seconds pendulum. For reasons of practical experimentation and to produce a length unit close to the foot, he favored a rod over a bob pendulum. A uniform cylinder beating seconds would be exactly 3/2 the length of a pendulum with all of its mass concentrated in a bob suspended at the end of a weightless rigid support. The specification of 45° latitude was a change from an earlier draft in order to be compatible with a recently made French proposal. Jefferson had previously specified 38°, a latitude lying in the middle of US territory; 45° was still within US territory, albeit barely.

Having recommended a standard, Jefferson presented two plans for units, one which retained the measures then in use but referred them to the carefully measured standard, and one which would involve a wholesale change to different units on a decimal scale. A complete overhaul would have great advantages, but would be, he recognized, very disruptive. He asks "is it the opinion of the representatives that the difficulty of changing the established habits of a whole nation opposes an insuperable bar to this improvement" [22]?

The plan for wholesale change was based on a unit defined as exactly 1/5 of the length standard. This unit would be called a foot, and it would be about ¼ inch shorter than the old foot [23]. (In this plan, some of the new units would be called by old names if they were similar in size to old units.) The divisions of the new foot in successive powers of 10 would be called the inch, line, and point; and its successive multiples of 10 would be the decad, rood, furlong, and mile. The unit of capacity (i.e., volume) would be a cubic (new) foot, called a bushel. One of the subdivisions of this unit Jefferson called a metre, defined as a cubic (new) inch (i.e., 1/1000 new bushel). The weight standard would be a metre of rain water, named an ounce. 10 of these would make a pound [22].

Jefferson's proposal for new measures includes the same three key aspects identified above in Wilkins's work—an invariable standard based on a natural phenomenon, decimal multiples and divisions, and an integrated system of length, volume and weight—as well as the ill-advised re-use of old names for new units. The fact that Jefferson had spent five years as a minister in France just before assuming the office of Secretary of State and the commission to report on weights and measures raises the question of possible continental influences on his thinking. Jefferson's contacts in France had included some of the savants who would play important parts in the French metric reforms. However, as C. Doris Hellman points out, decimal weights and measures were not actively discussed in France while Jefferson was there; she sees no need to attribute his exposure to such ideas to any specific source. Furthermore, Jefferson drafted his report for the House before receiving any communications about the discussions then beginning in France about reform of measures [23]. None of this is meant to suggest that Jefferson independently developed the ideas set out in his report—just that it is difficult to trace them to particular influences. After all, Jefferson was widely read and interested in natural philosophy before his diplomatic mission to France. Finally, the unsolicited plan developed by Waring—who had not just spent five years in Europe—demonstrates that personal contact with continental savants was not a prerequisite for designing a rational system of weights and measures.

One might assume that the US government opted for the more conservative of the options outlined in Jefferson's report, namely of relating old units to an invariable natural standard. In fact, neither option was adopted. The House tabled the report until December 1790. On 7 December Washington again named weights and measures as an important matter in an address to Congress. The House then assigned the report to a committee of the whole on 15 December and transmitted it to the Senate on 23 December. The Senate assigned it to a committee on 28 December. On 1 March 1791, the Senate committee deemed it inadvisable for the US to change its weights and measures while the French and the English were considering new systems of measures for possible adoption by those commercial nations. Discussions and postponements continued into early 1795, when Washington sent both houses of Congress a message about weights and measures from the French Republic's Committee of Public Safety transmitted from its minister to the US—essentially about the metric system. The House went so far as to pass a bill in May 1796 calling for units not very different from the foot and the avoirdupois pound then in use, and for experiments to define a length standard derived from a constant of nature. The Senate did not take up the bill, and the US entered the nineteenth century without a national system of weights and measures [23].

But the US did adopt a national currency. Currency was named along with weights and measures in Washington's 1790 address to Congress [20] and it was included in Jefferson's report [22]. The US established a mint and defined its coins in a decimal system of currency in the Coinage Act of 1792 [24].

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Chapter 2
Reform of Weights and Measures in Revolutionary France

Abstract Reform of weights and measures was one of the grievances mentioned frequently at the meeting of the Estates General of France in 1789. A project to establish a new system of measures on philosophical principles was begun not long afterward. The project underwent several changes early on, but after the early 1790s its shape changed little even as political turmoil brought violent ends to several of the individuals and institutions involved in it. Definitive meter and kilogram standards were legally adopted late in 1799, just after the fall of the first French Republic. This chapter lays out the story of reform of French weights and measures that led to the metric system as well as shorter-lived changes in organizing the day and the year.

2.1 Weights and Measures in the *Ancien Régime*

The variety of weights and measures in use in France in the late nineteenth century has often been noted. For example, the Englishman Arthur Young observed that there was some variation in the size of measures of land and grain in England … [1]

> but in France, the infinite perplexity of the measures exceeds all comprehension. They differ not only in every province, but in every district, and almost in every town; and these tormenting variations are found equally in the denominations and contents of the measures of land and corn.

Uniformity in weights and measures was frequently mentioned among the *Cahiers de doléances* (lists of grievances) collected in preparation of the meeting of the Estates General in 1789 [2]. (This body was summoned by King Louis XVI (1754–1793) in January of 1789—for its first sitting since 1614—and it convened in early May.) Calls for uniformity in measures appeared in the grievances of all three estates, the clergy, the nobility, and the rest. It would be a mistake to take the grievances from the third estate as a sign of popular dissatisfaction with weights and measures. In many of the *cahiers*, diversity in measures was presented as an obstacle to free trade. In other words, merchants and other economically powerful French subjects saw uniform measures to be in their interest [3].

In the summer of 1789, weights and measures were also on the agenda of the Académie royale des sciences. On June 27 the Académie appointed a commission

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to work on weights and measures [4], although there is apparently no record of what work, if any, that commission carried out. Meanwhile, important political changes were unfolding rapidly: in June the Estates General declared itself to be a National Assembly; in July the Bastille was stormed; and early in August, feudal privileges were declared abolished. Académicien Jean-Baptiste Le Roy suggested to the Académie that with the abolition of feudal privileges, there were no legal impediments to making measures uniform throughout the nation [2]. Feudal privilege was relevant because one of those privileges gave nobles control of the measures used in their territory.

2.2 Weights and Measures in the Constituent Assembly

The debut of the topic of weights and measures in the French National Constituent Assembly was in early February 1790. Mathieu Tillet (1714–1791) and Louis Paul Abeille (the latter, apparently, speaking) made a report on behalf of the Royal Academy of Agriculture and at the behest of the Marquis de Bonnay, chair of the Assembly committee on agriculture. Although they mentioned the possibility of basing a length unit on the seconds pendulum, they recommended a less exalted aim of uniform weights and measures that would be used by people rather than an unfamiliar set of measures based on philosophical principles. They invoked measures from an ideal past, mentioning Charlemagne several times. Imposing Paris measures on the entire nation would be a feasible way of achieving uniform measures. The presentation appears to have prioritized commerce over academic science [5].

Also in early February, Claude-Antoine Prieur (1763–1832) presented a report on measures to the assembly [6]. Prieur, also known as Prieur du Vernois or Prieur de la Côte-d'Or, prepared his memoir at the suggestion of the prominent chemist Louis-Bernard Guyton de Morveau (1737–1816), his father's cousin. Prieur, in Dijon, was probably not aware of the Académie committee constituted in Paris; however, he included the main features of measures designed on philosophical principles: an invariable standard from nature, decimal divisions, and dependence of units of capacity and weight on that of length. He suggested that science, rather than using units passed on to it from commerce, devise units and pass them on to commerce to benefit both science and commerce. He discussed an arc of meridian and a seconds pendulum as possible length standards, favoring the latter measured at a specific location. Prieur's 1790 proposal was not adopted. He would, however, be influential in development of the metric system later in the decade [2].

The presentation to the National Assembly that is commonly credited with beginning the creation and adoption of the metric system is that by Talleyrand distributed in March of 1790 [7, 8].[1] Charles-Maurice de Talleyrand-Périgord (1754–1838) was at that time Bishop of Autun and a member of the Assembly. He called for seizing

[1] John Riggs Miller's book on weights and measures [8] reprints Talleyrand's proposal in French as well as an English translation of it.

the revolutionary moment to make a clean break with measures of the past. But this was more rhetorical than revolutionary, for his proposal was more modest, limited to naturalization and unification of units quite close to some then in use. Talleyrand outlined two possible natural length standards, the 1/60,000 of a degree of a meridian at 45° or (the preferred alternative) the length of a seconds pendulum at 45°.[2] The latter would define the aune, which would be subdivided into feet, inches, and lines as already done. The pound would also be similar to that then in use, but would be defined by a cube of water measuring three of the newly defined inches on a side at 14.4° Réaumur (equivalent to 18 °C or about 64 °F).

Talleyrand's presentation ended with a draft decree, which the Assembly adopted in May 1790. The Assembly decreed that the King be asked to direct that units currently in use within the realm be collected for study; to request the King of Great Britain to have the Royal Society work with members of the Académie to measure the length of a seconds pendulum at 45° to be the basis of an integrated system of units; and to have replicas of the new measures be distributed throughout the country to replace the old units six months after distribution. Louis XVI approved the decree in August 1790. By this time, though, the British foreign secretary had already rebuffed a proposal for cooperation on this matter made by the French ambassador [2].

The system that Talleyrand proposed and that the Assembly and King adopted was not a decimal system. Charles Gillispie writes that Talleyrand consulted with savants before preparing his address, including the Academy's permanent secretary, Condorcet (Jean-Antoine-Nicolas de Caritat, Marquis de Condorcet, 1743–1794). Gillispie found phrases in papers of Condorcet's too similar to some of Talleyrand's to be coincidence. Gillispie wonders if Talleyrand ignored Condorcet's advice about decimalization and nomenclature with an eye toward popular opinion or perhaps to increase chances of cooperation with Great Britain [2]. As noted, Talleyrand's proposal called on the King of France to propose cooperation to his British counterpart. Talleyrand was himself in correspondence with Miller in England [8].[3]

Gillispie writes that the decree based on Talleyrand's proposal moved the work of measures reform from the Assembly Committee on Agriculture and Commerce to the Académie [2]. In June 1790 the committee on Agriculture, which had endorsed Talleyrand's draft decree before the Assembly adopted it, sent its files to the Académie. In July 1790 an Académie committee of Laplace, Borda, Coulomb, Tillet, and Lavoisier (chair) took up the matter. This was a stellar committee, as should be apparent from the fact that a majority have names that appear in math and science

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[2] By this time, it was known that the earth was not a perfect sphere, that it bulged slightly at the equator. This is responsible for the variation with latitude of the length of a seconds pendulum noted in Sect. 1.4. It also makes degrees of latitude (i.e., along a meridian) differ slightly in length with latitude.

[3] Miller published two letters from Talleyrand in his book [8], and he says that Talleyrand graciously credited his speeches in Parliament with inspiring him to raise the subject in the National Assembly (p 28). It seems to me that Miller reads too much into Talleyrand's statement that he was aware of Miller's efforts and that he felt it his duty to raise the same matters to the National Assembly (pp 58, 75).

textbooks more than 200 years later. Pierre-Simon de Laplace (1749–1827) is the mathematical physicist for whom an operator in differential calculus and a probability distribution are named. Jean-Charles Borda (1733–1799) improved a surveying instrument, the repeating circle, to such an extent that it is often called the Borda repeating circle. Charles Augustin Coulomb (1736–1806) is known for his eponymous electrical law, and the SI unit of charge is named for him. Tillet is least known today: he was in the Académie as a botanist, but he was also an agronomist and he had had some experience in the 1760s with having copies of a surveying standard made and distributed. Antoine-Laurent de Lavoisier (1743–1794) was the leading chemist of the time, responsible for the oxygen theories of combustion, calcination, respiration and—since discarded—acidity.

The idea of using a decimal scale entered the official discussion in a report by an Académie committee that dealt mainly with reforming currency. That committee, comprised of Borda, Joseph-Louis Lagrange (1736–1813), Lavoisier, Tillet and Condorcet, reported that not only ought currency to be decimally denominated, but so ought all weights and measures [9].

In March 1791, yet another Académie committee reported to the National Assembly its recommendation of a length standard, giving the metric project the basic shape it would have over most of the rest of the decade. This report preferred a different length standard—not the pendulum but a quarter of a meridian of the earth. It proposed the quarter meridian as the actual length standard and 1/10,000,000 of it as the practical length standard. It proposed a survey of the meridian arc from Dunkirk through Paris to Barcelona to determine the length of the quarter meridian (the whole length being impractical to measure). That was a sufficiently long segment that passed through the 45th parallel and had the same elevation at both ends (namely sea level) to make it representative of the whole, the report asserted. In addition to length, the report also proposed using a decimal scale for angular measurements: a quarter circle (right angle) would be divided into 100 *grades*, thus making distances along the meridian easily convertible to differences in latitude. Finally, it proposed a weight standard based on the weight of a specified volume of distilled water at its freezing point [10]. Before the end of March 1791, the National Assembly endorsed this proposal and the King approved it [11]. This law charged the Académie with nominating commissions to carry out the necessary work.

Condorcet sent Thomas Jefferson a copy of this Académie report, and Jefferson candidly wrote that he would not have approved it. For one thing, it assumes that the 10% of the meridian to be measured has the same shape as the 90% not measured. For another, the proposed standard effectively becomes the property of France, because only France has a meridian of such length passing through the 45th parallel and level (at sea level) at both ends [12]. In effect, Jefferson reaffirmed the choice he had made in his own report on weights and measures based on the belief that geodesic standards were impractical [13].

The Académie, on the other hand, gave as its main reason for rejecting a pendulum as a length standard the opinion that it was inappropriate to base a unit of length on a unit of time, and an arbitrary one (the second) at that.[4] Historians of the metric system have disagreed over whether this recommendation was made entirely in good faith. John Heilbron, for example, finds the stated reasons for preferring the meridian over the pendulum unconvincing. Furthermore, the Académie received a large government grant to carry out the work, including for the purchase of high-quality instruments designed by Borda [14]. Where Heilbron sees grantsmanship at work, Gillispie does not. In fact, Gillispie sees the connection between celestial and terrestrial navigation—the correspondence between angles and distances only hinted at here but spelled out by Laplace in a later report—as a reason for believing Laplace to have been very influential in the choice of the meridian as the standard [4].

The Académie named several small committees to take up various tasks required to implement the plan. The survey of the meridian was put in charge of Jean-Dominique Cassini (1748–1845), Pierre Méchain (1744–1804) and Adrien-Marie Legendre (1752–1833). These three had been part of an Anglo-French surveying project in 1787 to connect previous surveys of their respective territories across the English Channel. Cassini was the fourth and last of the dynasty of astronomers of that name known for their contributions to the cartography of France. At this time, Cassini was director of the Paris Observatory, having succeeded his father in that post. He withdrew from this project in 1792, before the survey team went into the field, and in May 1792 he was replaced by Jean-Baptiste Delambre (1749–1822). Legendre, a mathematician after whom a set of polynomials is named, had withdrawn in March 1792. Méchain and Delambre were left to carry out the survey. They went into the field in late June 1792, Delambre heading north and Méchain south. The segment assigned to Delambre was about twice as long as that assigned to Méchain, but it was expected to be easier. Delambre's segment had been surveyed a few decades earlier, and it was expected that he and his assistants would use mainly the same observation points (hills and steeples, for example) as the earlier survey. Méchain's segment included difficult terrain (the Pyrenees) as well as territory not previously surveyed in neighboring Spain [2].

Other committees constituted in 1791 included Borda and Cassini to measure the seconds pendulum; Lavoisier and René-Just Haüy (1743–1822) to carefully determine the density of water at a fixed temperature; and Tillet, Mathurin-Jacques Brisson (1723–1806), and Alexandre-Théophile Vandermonde (1735–1796) to compare provincial units to those of Paris. (Haüy is best known today for work in characterizing the crystals of minerals. Vandermonde was a mathematician who studied determinants among other topics.) The pendulum would not be the basis of the system, but it could be useful as a secondary standard. Experiments on the pendulum were carried out in the summer of 1792. Haüy and Lavoisier made their report on the density of water in January 1793. No systematic inventory was ever made of provincial units; Tillet died in December 1791 and Vandermonde in 1796 [2].

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[4] Metrologists of the twentieth and twenty-first centuries would disagree with this reasoning. Since 1983, the definition of the meter, base unit of length in the SI, is the distance that light travels in vacuum in 1/299792458 s.

Meanwhile, precise and expensive instruments were being prepared for the survey. In August 1791, the government appropriated 100,000 francs for the Académie for instruments and initial expenses [15]. These instruments included new Borda repeating circles graduated into 4000 angular divisions (that is, with decimally divided right angles) as well as measuring rods of the toise of the Académie (the length standard used for previous geodesic surveys). The instruments were calibrated in late May and early June 1793 [2].

While experimental work was being done and prepared, another committee (Borda, Lagrange, Condorcet and Laplace) was at work on nomenclature for the new system. In July 1792 they proposed new terms and some systematic prefixes. In particular, they recommended *mètre* for the length unit—still the name in French and transparently cognate to the meter (US) and metre (UK). For long distances, they proposed a *millaire* of 1000 m. For lengths shorter than a *mètre*, they proposed to append prefixes derived from the words for tenth, hundredth, and thousandth in French (and most romance languages), giving decimeter, centimeter and millimeter. This committee also considered a unit appropriate for measuring land area, pointedly rejecting the name *arpent* then in use. A square 100 m on a side seemed an appropriate size, and they gave this unit the name *are* to suggest area; its decimal divisions would use the systematic prefixes, yielding deciare and centiare [16]. The committee selected an area unit that is still convenient for land measurement, but their *are* is today's hectare.

The same committee reported on the topic of weight in a report in January 1793, including a summary of the work of Lavoisier and Haüy on measuring its density. The unit they proposed was a cubic decimeter of distilled water, which they would call a *grave*. The same prefixes proposed for linear measures would be used to designate divisions of this unit [17]. This report specifies no temperature to define the unit.

2.3 Weights and Measures Under the Convention

While work was proceeding on the project of defining new measures, seismic political events continued to occur. In the fall of 1791, Louis XVI accepted a constitution, the National Constituent Assembly closed, and the National Legislative Assembly opened. The constitutional monarchy did not last long: the monarchy was overthrown in August 1792, a republic proclaimed in September governed by a body called the National Convention, and in January 1793 citizen Louis Capet, former King of France, was executed. By February 1793, France was at war with Austria, Prussia, Britain and the Netherlands.

All of this upheaval dramatically affected the survey teams. When Delambre's group built scaffolding to assist observations, local residents tore them down. Some of the tall church buildings they had hoped to use had been damaged. Local authorities took them into custody for sending signals by torchlight from hilltops. Their documents, signed by the King, were worthless from late 1792 [2]. And that was only the beginning of the obstacles eventually overcome by both Delambre's and

Méchain's teams. The survey turned into a seven-year odyssey whose story is told in great detail by Ken Alder's book *The Measure of All Things* [18].

The time required to determine standards for the new units was trying the patience of government authorities even during the constitutional monarchy. In April 1792 interior minister Jean-Marie Roland de La Platière proposed establishing provisional measures to be used until the painstaking work of establishing definitive standards could be completed. In December the Convention joined four members of its Committee of Public Instruction to the Académie group working on the new measures. Among these were Prieur and the Strasbourg mathematician Louis-François-Antoine Arbogast (1759–1803), both of whom had been elected to the National Assembly and now served in the Convention. The Académie responded to Roland's proposal early in 1793 that a provisional meter could be determined from data from a 1740 survey [2].

The Académie sent a report to the Committee of Public Instruction in the spring of 1793 describing progress to date. This report says that the Académie reconsidered the systematic nomenclature it had previously proposed, noting that the prefixes gave rise to unit names that were long and that sounded similar. So it returned to an idea it had previously considered but rejected, namely the use of short names easily distinguished from each other to denote the (still decimal) divisions and multiples of base units. The report does not withdraw the previous nomenclature, but it says that it prefers the second to the first. In the second nomenclature, the divisions of the quarter meridian of length are, successively, the *décade*, *degré*, *poste*, *mille*, *stade*, *perche*, *mètre*, *palme*, *doigt* and *trait*, each 1/10 of the previous one. Note that the *degré* suggests the correspondence between latitude and distance along the meridian, for the *degré* corresponds to a "decimal degree" of latitude (that is, 1/100 of a right angle) and a distance we would call 100 km. The names proposed for units of capacity in the second nomenclature, again each 1/10 of the previous one, were *tonneau* (a cubic meter), *sétier*, *boisseau* and *pinte*. The same measures in the first nomenclature were *muid*, *décimuid*, *centimuid* and *pinte*. The successive weight units in the second nomenclature were *millier* (weight of a cubic meter of water), *quintal*, *décal*, *livre*, *once*, *drâme*, *maille* and *grain* [19]. Note that many of the names of the second nomenclature were not only simple, but familiar—old names for new units.

Arbogast sent the Convention a draft law [20] to establish provisional weights and measures in late July 1793, and the Convention adopted it on August 1. The law established a new system of weights and measures that would become mandatory as of 1 July 1794. The names of the units mainly followed the initial recommendations of the Académie, retaining the prefixes deci- and centi-, but opting for a new name for a thousandth of a unit.[5] The law designated what we would call a base unit for length (meter), land area (are), capacity (pinte) and weight (grave), and it gave values for each unit in terms of units then in use in Paris [21]. The names of length units were those described in Sect. 2.2 above, with the addition of the *grade* or *degré décimal*. For capacity, the *pinte* (a cubic decimeter) was the base unit, and the larger unit (a cubic meter or 1000 *pintes*) was called a *cade*. The base unit of weight was the *grave*,

[5] Except that a thousandth of a meter was called a millimeter.

the weight of a cubic decimeter of water. A larger weight unit equal to 1000 *graves* was called a *bar*, and a smaller one (1/1000 *grave*) was called the *gravet*. The law also established a unit of currency, the *franc*, equal to a *centigrave* of silver [21].

The law charged the Académie des sciences (no longer royale) with working with the Committee of Public Instruction to make standards for the new units, and with distributing copies of the standards to the provinces [21]. But one week after the passage of the law, the Académie and other learned societies were suppressed. Before long, the Convention constituted a temporary commission on weights and measures consisting of the former académiciens already working on the project along with Arbogast, Prieur (now a member of the Convention's Committee of Public Safety), and Antoine-François de Fourcroy (1755–1809), a prominent chemist and member of the former Académie now in the Committee of Public Instruction [2]. Larger political forces had caught up with the Académie, and they would enmesh several of its members in the coming months.

2.4 The Republican Calendar and Decimal Time

Gilbert Romme (1750–1795), a mathematician, astronomer and deputy of the Convention, presented a report to that body in September 1793, proposing a new calendar for the French era. One of the first decrees of the National Convention that had declared France to be a republic in September 1792 was to date its subsequent public acts with respect to the date of the establishment of the Republic. The Committee of Public Instruction appointed a small group in December 1792 to work on a proposal for a calendar. Romme asked the Académie for some assistance early in 1793 and apparently met some members, but no official record was taken at the time. Romme also addressed a query to Lavoisier in September shortly before issuing the report [22].

The proposal contained within the report observed that it was fitting that the first day of the Republic had been the autumnal equinox, when day and night were equal. Division of the year into 12 months was consistent (roughly) with natural lunar cycles, but there was no good reason to make the months unequal in length: let them all have 30 days. There would be five extra days per year—six every fourth year—at the end of the year not belonging to any month. The seven-day week was described as arbitrary and inconvenient, dividing evenly into neither the month or the year, and it gave priests power over the religious day of rest. *Décades* (10-day periods) would be more convenient, exactly three in each month. There would be a day of rest at the end of each *décade*. Within the day, division into 24 hours of 60 minutes of 60 seconds was also arbitrary and inconvenient; partitioning the day into 10 equal intervals to be further subdivided decimally would be more rational [22].

The Convention put Romme's report into law on 5 October 1793. The era of the French was to be counted from 22 September 1792, the date of the foundation of the Republic and the date of the autumnal equinox. Henceforth the "common era [l'ère vulgaire]" was abolished for civil purposes. Days were to be counted from

Table 2.1 The months of the Republican calendar and the seasonal attributes their names evoke[6]

Autumn	*Vendémiaire*	*Brumaire*	*Frimaire*
	Grape harvest	Fog	Hoarfrost
Winter	*Nivôse*	*Pluviôse*	*Ventose*
	Snow	Rain	Wind
Spring	*Germinal*	*Floréal*	*Prairial*
	Budding	Flower	Meadow
Summer	*Messidor*	*Thermidor*	*Fructidor*
	Corn	Heat	Fruit

midnight to midnight, and the day on which the fall equinox was observed in Paris was to be counted as the first day of the new year. This change of the start of the year required a re-dating of acts passed in 1793 before September 22 (such as the act that established the provisional system of weights and measures); they would now be considered to belong to the first year of the Republic rather than its second. The law included the decimal division of the day, but that provision would not go into effect until the first month of year three (that is, after about a year) [23]. The law did not include names for the new months. Romme would have named the months and the days after revolutionary episodes or virtues such as the Bastille and the red cap [22].

The poet and dramatist Philippe-François-Nazaire Fabre d'Églantine (1750–1794) was responsible for the nomenclature of the new year, which was adopted by the Convention on 24 October 1793 (or 3 *brumaire an* II in the new style). The names of the months, given in Table 2.1, were naturalistic and seasonal. The days of the decade were numerical: *primidi* (first day) through *décadi* (tenth day). The extra days at the end of the year were called sans-culottides [22].

The definitive law on the new calendar was passed on 4 *frimaire an* II (24 Nov 1793). It is a fairly lengthy document, which includes an almanac of republican year II (Fig. 2.1). The almanac gives astronomical data related to the sun and moon in decimal hours [24].

Each day of the year had a name assigned to it, typically of a flower, plant, animal or mineral [22]. These day names were not used in giving civil dates, but they seem to have replaced the names of saints and religious feasts with which the Gregorian calendar had been adorned. In this respect, at least, the 1788 *Almanach*

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[6] The months have been rendered by various English wags as
Freezy, Sneezy, Breezy, Wheezy,
Showery, Lowery, Flowery, Bowery,
Snowy, Flowy, Blowy, Glowy
or
Snowy, Flowy, Blowy,
Showery, Flowery, Bowery,
Hoppy, Croppy, Droppy,
Breezy, Sneezy, Freezy.

The latter version has been attributed to George Ellis (1753–1815), a satirical poet and member of parliament, but I could not locate the original.


THERMIDOR.

ONZIÈME MOIS.

Jours du Mois.	Noms des jours de la Décade.	Lever du Soleil.		Coucher du Soleil.		Temps moyen au midi vrai.			Distance du Soleil à l'Équateur.		
		H.	M.	H.	M.	H.	M.	S.	D.	M. Boréale.	S.
1	Primedi.	1	75	8	24	5	04	03	23	11	26
2	Duodi.	1	76	8	24	5	04	08	22	88	89
3	Tridi.	1	77	8	23	5	04	11	22	69	10
4	Quartidi.	1	78	8	22	5	04	14	22	46	30
5	Quintidi.	1	78	8	21	5	04	17	22	24	41
6	Sextidi.	1	79	8	20	5	04	19	22		
7	Septidi.	1	80	8	19	5	04	20	21	77	22
8	Octidi.	1	81	8	18	5	04	20	21	52	72
9	Nonidi.	1	82	8	17	5	04	20	21	27	59
10	Décadi.	1	83	8	17	5	04	19	21	01	91

Fig. 2.1 Part of the almanac of French Republican year II, showing solar data for the first *décade* of the month of *thermidor* from Romme's Calendrier de la République Française, courtesy of Gregory Girolami and Vera Mainz. Note that sunrise and sunset are given in decimal hours and minutes. The rightmost column gives the angle of the noonday sun with the equator in decimal degrees, minutes and seconds

des Honnêtes Gens of Sylvain Maréchal [25] seems to have been a real precursor of the republican calendar. Maréchal's almanac associated each day of the year with one man (sometimes two)—very few women were on the list—from a wide range of human activities: philosophers, writers, poets, rulers, natural philosophers and even a few religious figures. For example, Jesus and Newton share December 25. Maréchal began his year not with January but with March, following the Roman tradition. And he styled the year as the first of the reign of reason. In these respects, it was a "Revolutionary Calendar before the Revolution" [26].

The definitive law on the calendar also included tables that converted times of day between the new decimal and the old duodecimal/sexagesimal scales. The terminology of the divisions of the day used old terms for new values: the day was divided into 10 hours, each of which was divided into 100 minutes, which were in turn divided into 100 seconds (and these were divisible, in principle at least, into 100 thirds) [24].[7]

Decimal time was never widely adopted, and it was officially discarded in a law of 18 *germinal an* III (7 April 1795) after being in effect for less than a year. As

[7] Etymologically, the words minute and second as divisions of the hour (or of the degree) derive from the Latin phrases *pars minuta prima* (the first small part or division) and *pars minuta secunda* (the second small division). The "thirds" here refer not to 1/3 of a second but to the third small division of the hour.

Fig. 2.2 Republican clock (public domain, https://commons.wikimedia.org/w/index.php?curid=276100)

Gillispie noted, people were not going to discard their timepieces [22]. Figure 2.2 shows the face of a clock designed to keep decimal time (upper dial with 10 divisions circled once per day), traditional time (lower dial with 12 divisions circled twice per day) and the republican date (small dial at left). Revolutionary symbols adorn the rest of the face. The republican calendar outlasted decimal time. Indeed, it lasted longer than did the Republic—in fact, if not in name.[8] France returned to the Gregorian calendar on 1 January 1806. In fact, the seven-day week had begun to emerge into public view in April 1802, after a concordat between the French government and the Roman Catholic church had been promulgated [27].

From the perspective of the early twenty-first century, when almost all of the world uses metric measures while the French republican calendar and decimal time have been extinct for more than 200 years, it is tempting to wonder whether these attempts to reorganize time really constitute part of the metric system or were simply a side show. I have deliberately put the question in a way considered poor practice by historians, alluding to developments that occurred long after the republican calendar and clock were enacted to question whether their development was or was not an integral part of the weights and measures story. But now I will consider the more properly historical version of the question: how closely related were the systems as the events unfolded?

It is fair to say that the metric system and the calendar had similar political sponsors in 1793 but different scientific support. As noted in the last section, the Convention Committee of Public Instruction was inserting itself more actively into the work of

[8] Napoléon Bonaparte (1769–1821) was given the oxymoronic title Emperor of the Republic in May 1804 after having taken power as First Consul in late 1799.

the Académie and then the temporary commission on weights and measures. The calendar also was proposed to the Convention under the auspices of that committee. The calendar and decimal time had very little input from leading savants, though. In contrast to the reform of weights and measures, the reorganization of time benefitted from neither a well-considered intellectual tradition advocating such reforms (see Chap. 1) nor active experimental work by leading natural philosophers.

It seems to me that the rhetoric and symbolism around the calendar was more overtly political than that around reform of weights and measures. The proposal of the calendar was heavy on symbolism linking it to the exalted Republic. And although the names of the days of the year evoked nature, it did so in a more romantic mode than the demand of the savants for a standard drawn from nature. That is, the designers of the calendar valued nature in quite a different way than did the savants. George Gordon Andrews cites the calendar's clash with Roman Catholic practices as a source of much resistance to it. If the advocates of the calendar had not been so intent on reducing the influence of the church, the rational advantages of the calendar might have won the day, he argues [27]. Hector Vera's stimulating article about decimal time focuses on nineteenth- and twentieth-century opportunities for converting to decimal time more than on the failure of such a conversion to take root in the eighteenth century. Still, he argues that measures of time were not in such disarray as other measures, so the benefits of decimalization were less tempting to those who were concerned with measurement [28]. In sum, it can be argued that the metric reform responded to a desire for change expressed by important segments of society, including merchants and savants, and enlisted the latter in the project. By contrast, the calendar and the clock did not appear to meet a social need, and the calendar presented a clear challenge to the Catholic church and its adherents.

As will be apparent in the next chapter, the metric system was not exactly a success in early nineteenth-century France, and the role of savants in designing the system may be to blame for its early floundering. Still, there seems to be enough of a difference in motives and social support between the reforms of measures and time to consider the latter to be rather peripheral to the former.

2.5 The Metric Project and the Reign of Terror

The phase of the French revolution known as the Reign of Terror is typically dated to 5 September 1793 when terror was proclaimed in the National Convention to be the order of the day. The arrest of Maximilien de Robespierre (1758–1794) on 27 July 1794 and his execution the next day are generally considered to mark the end of the Terror. Gillispie notes that almost no organized science was carried out during this period except for war work [22].

The Convention tried to keep the project to establish provisional metric measures moving by appropriating money to have standards made and distributed throughout the nation and charging the temporary commission with quality control [29].

The Committee of Public Safety purged the commission on weights and measures of some of its most prominent members—Borda, Lavoisier, Laplace, Coulomb, Brisson, and Delambre—in late December 1793 [22]. This order is in the handwriting of Prieur, and Delambre believed that it was at his instigation. Prieur had attended the meetings of the temporary commission, and in the political discussions that took place at them he, a representative of the regime, was frequently in a minority and often alone [2]. The order reached Delambre in the field about a month later, and he returned to Paris from the meridian survey [18]. Laplace and his family had left Paris for the countryside near Melun before the purge of the temporary commission [4]. Shortly afterwards Borda and Coulomb retreated to a country house near Blois that Coulomb had bought earlier in the year from Lavoisier [22].

Their troubles paled compared with those of Lavoisier, who had already been arrested before he was removed from the commission on weights and measures. Indeed, Delambre believed that Prieur moved to purge the commission because it had petitioned the Convention's Committee of General Security to release Lavoisier on parole so that he could continue work on the project [2]. Lavoisier's trouble was due to his connection to the Ferme générale, which was, in effect, a powerful private corporation to which the monarchy had contracted collection of taxes and duties. Lavoisier was a partner of the Ferme as was his father-in-law. The National Assembly had abolished the Ferme in 1791 and given it until the start of 1793 to wind up its financial affairs. The partners who could be located were arrested in late November, and Lavoisier and his wife, Marie-Anne Pierrette Paulze (1758–1836), turned themselves in. In May 1794, a trial of sorts was held for the 28 partners in custody. They were convicted and on the same day executed at the Place de la Révolution [22].

By this time Condorcet, one of the earliest members of the Académie to concern himself with weights and measures, was also dead. In June 1793 he had anonymously but not secretly condemned the new constitution, and in July the Convention had ordered his arrest. Friends hid him in Paris for several months while he was condemned to death in absentia. In March 1794, the penalty for harboring outlaws could be extended to those who sheltered them. At that time Condorcet attempted to flee Paris. He was captured late in March and found dead in his cell the next day. Some believe that he committed suicide, others that he suffered a fatal stroke [22].

Amidst the turmoil of the individuals and institutions of the metric project, preparations continued for the introduction of the provisional meter. The first exposition of the system for widespread public distribution was a manual for instruction in the new weights and measures published in the spring of 1794 and prepared primarily by Haüy [15]. The book lays out the system essentially as set forth in the law of 1 Aug 1793 albeit in greater explanatory detail and with extensive conversion tables. One expansion is the section on measurements of angles. This section retains the old terminology of degrees, minutes and seconds and even extends it to thirds and fourths,making each smaller than the previous one by a factor of 100 rather than 60. It spells out the correspondence between angular measures of longitude and distances: a decimal degree along a meridian corresponds to 10,000 m, and a decimal fourth to a millimeter. In the capacity (volume) section, the unit equal to a cubic decimeter is called a *cadil* rather than retaining the old name *pinte* used in the law of 1 Aug 1793. This manual also addresses divisions of the thermometer, a topic not taken up in any of the laws to date. It divides the scale between the freezing and boiling points of water into 100° rather than the 80° of the "ordinary" thermometer [30].[9]

2.6 Resumption of the Project After the Terror

The metric project was in abeyance for about a year—longer if one does not count the instruction manual, which did nothing toward making usable standards available. Late in 1794, the Committee of Public Instruction invited Prieur to take the project in hand. He and a small group presented a report a few months later, and that report was the basis of the law on weights and measures of 18 *germinal an* III (7 April 1795) [31]. The new law postponed the date of obligatory adoption of the new units (a date that had arrived some nine months earlier) until a date yet to be determined by the Convention; meanwhile, citizens were invited to show their devotion to the unity of the Republic by using the new units in their calculations and commercial transactions. The law restored the meridian survey under Delambre and Méchain. Meanwhile it abolished the temporary commission on weights and measures and instituted a three-member agency on weights and measures to oversee completion of the project, including having standards made and distributed and instructing the public. Legendre was named head of the agency a couple of days later [32].

Nomenclature is one of the most apparent features of the new law and an area in which it departs considerably from the 1793 law. The 1795 law claims to be definitive on the subject, and for the most part the nomenclature proposed here persisted, although the general surname for the system, republican, did not. Of the specific names listed in the law—*mètre*, *are*, *stère*, *litre*, *gramme* and *franc*—only *mètre* survives from 1793. The 1795 *are* for land area has the same size as the current are, 1/100 of the 1793 *are*. The *stère* is new, a unit of volume intended to measure firewood; it is a cubic meter. The *litre* and *gramme* have essentially the same value as the current units of those names. The *franc* as a unit of currency replaced the *livre*. Divisions (*centimètre* and *décimètre*) and multiples (*décamètre*, *hectomètre*, *kilomètre* and *myriamètre*) of the meter were spelled out, and divisions and multiples of other units could be formed the same way. And, by the way, mandatory use of decimal time was suspended indefinitely [31, 32].

Early in the summer, Brisson and Borda verified four provisional meters that would be used to make copies. A law passed in September (1 *vendémiaire an* IV) set a schedule for progressive mandatory use of the new units. The *aune* would be phased out in Paris in three months (on 1 *nivôse*) and 10 days later in the rest of the Department of the Seine. Meanwhile the survey continued, although its results were not needed for the provisional measures. The Committee of Public Safety ordered

[9] The "ordinary" temperature scale is one known today as the Réaumur scale. The centigrade temperature scale had been in use earlier in the eighteenth century elsewhere in Europe.

the continuation of the survey during the spring of 1795 and renewed the order in spring 1796 [15].

2.7 Completion of the Project: The Definitive Meter

The survey teams would not be finished until late 1798. Near the middle of the year, foreign minister Talleyrand (Fig. 2.3)[10] invited friendly and neutral foreign governments to a conference in Paris to begin in early October. The purpose was to complete and review the work needed to determine definitively the new units. Gillispie has pointed out divergent opinions on the value of this congress, some calling it arguably the first international scientific conference [33] and others regarding it as a rubber stamp. He takes a middle ground, regarding the diplomacy as hollow but the science solid. There is good reason to believe that the French government intended the congress to be window dressing. Most of the invited nations might be considered French puppet states, a list of republics left in the wake of French armies: the Batavian, Cisalpine, Helvetian, Ligurian and Roman Republics. None of the great powers of Europe other than France was invited. Some of the leading French scientists believed it was to be propaganda to give the system an appearance of international if not universal applicability. But the attendees were leading natural philosophers in their countries, and together with members of the French Académie des sciences (reconstituted under the umbrella of a new *Institut de France*) they carried out calculations and experiments to produce definitive standards of the meter and kilogram [31].

The congress began not in October but in late November because the survey team did not return to Paris until then. Three technical tasks were divided among three subcommittees. One was to go over the data and carry out the calculations of the meridian survey. One was to determine the length of the platinum measuring rods used to measure the survey's baselines. The third was to determine the weight of a kilogram. In effect, the survey determined the length of the meridian arc in units of the platinum measuring rods. Those rods were found to be two toise each (two of them indistinguishable in length from that standard and the other two different by a handful of parts per million such that the sum of the four rods—in effect the unit for the baseline—was indistinguishably different from eight toise. The definitive meter was 443.296 lignes, compared to 443.444 for the provisional meter. Analysis of the survey data in detail showed that the length of a degree of longitude did not decrease smoothly as one moved southward: the shape of the earth was more complicated than a simple oblate spheroid. Determining the weight of the kilogram required painstaking measurements of volume as well as of weight in air, in vacuum,

[10] When we last saw Talleyrand early in the revolution, he was Bishop of Autun and a member of the National Assembly in the last days of the monarchy. Now he is foreign minister of the republic under the Directory. He would go on to serve as a diplomat under Consul and then Emperor Bonaparte and then under the restored monarchy.

Fig. 2.3 Talleyrand caricatured in 1815 as the man with six heads [34], courtesy Gallica, Bibliothèque nationale de France

and in water. The procedures were considerably more precise than those employed by Lavoisier and Haüy in defining the provisional grave, but there was very little difference in the result. The definitive kilogram was 18,827 grains versus 18,841 for the provisional grave [31]. This value made use of the fact, discovered in the process of these careful measurements, that water has its maximum density at 4 °C. Noting that the state of maximum density is a unique constant point, the commission set the weight of the kilogram as a cubic decimeter of water in this state rather than at its freezing point (as had been previously specified) [35].

The Congress reported its results to the *Institut*, which had standards made. Iron and platinum standards of the meter and kilogram were presented to the two houses of the French legislature in June 1799. The platinum standards were housed thereafter in the National Archives. Legislation defining the new standards as the definitive length and weight standards of the nation was passed on 19 *frimaire an* VIII (9 Dec 1799). Other than replacing the provisional with the definitive, this law affirmed the 1795 law. The definitive metric law passed under the Consulate—for Napoleon had taken power in a coup about a month earlier—and during Laplace's six-week stint as Minister of the Interior [31]. The project spanned the French revolutionary decade.

The law establishing the definitive meter and kilogram also called for a commemorative medal to be struck bearing the universalizing words "*À tous les temps, à tous les peuples* [for all times, for all peoples]" [36]. Would all peoples embrace the new measures? Would the French?

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Chapter 3
Metrication in France and Beyond: The Meter Goes International

Abstract Adoption of the new metric measures was slow even in France. Compulsory use was resisted and concessions were made that restored some of the names and divisions of older French customary units. The system developed in the 1790s took firm hold in France only after 1840. It was gradually adopted in other nations as well. In 1875 the Metre Convention established institutions that put the metric system under international governance.

3.1 Metrication in Post-revolutionary France

The *Oxford English Dictionary* defines metrication as "conversion to the metric system of weights and measures; the adoption of the metric system." It traces the word back only to 1965 as a coinage by the British National Physical Laboratory—after consultation with an Oxford dictionary editor no less [1]. The term has been used extensively in the UK and the US in connection with those countries' moves toward the metric system. (The adoption of the metric system in the UK was announced in 1965.) The word will be used here to describe similar phenomena, albeit a century and more before the term was coined.

Many historians of the metric system report that the new measures were widely resisted, in commerce at least, from the time of their introduction. John Heilbron reports that a law requiring the new measures to be used in land transactions and building contracts complicated the work of artisans, who would take measurements and buy supplies in old units and convert to new measures for official paperwork [2]. Even the Paris bureau of weights and measures sometimes reverted to the old measures, such as when one of its invoices gave the weight of a shipment of metric standards in pounds [3].

Ken Alder attempted to understand the reasons for the failure of French artisans and merchants to adopt the measures that were, after all, designed in response to complaints from that very group about the old units. He argues that the reforms that French citizens were given were not the reforms they asked for. Uniformity of weights and measures was their principal demand. Savants added several aspects to that demand, particularly after the Académie was formally charged with working to

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implement the 1790 decree on the subject. In particular, selecting a standard from nature, making the units relate to each other, making divisions and multiples decimal and inventing a systematic nomenclature were aspects of the reform that appealed to the savants [3]. (Recall that a standard from nature was already part of the 1790 presentation of Talleyrand, which was the basis for the 1790 decree; however, that presentation was apparently influenced by Académie members. See Sects. 2.2 and 2.3.) In light of the intimate involvement of the French scientific establishment in the development of the new units, it should come as no surprise that most branches of French science adopted them quickly. By the time the report on definitive metric units was presented to the *Institut de France*, metric units were already routinely used there [4].

The expression of multiples or divisions of units as powers of 10 was intended to make calculations involving the new units simpler by permitting measures to be expressed as a single number. As an illustration, what is the area of a rectangular piece of cloth 1 yard, 2 feet and 3 inches wide by 3 yards, 2 feet and 1 inch long? If I had to make the calculation, I would express the sides of the rectangle in a single unit, and I would choose inches to avoid fractions. After converting the length and the width to inches, I would multiply them together to get the area in square inches. More arithmetic is needed if the result is desired in square feet or square yards. In metric units, though, even if given a measurement as 1 m, 2 dm and 3 cm, it is trivial to express the measurement as a single number: 1.23 m or 123 cm. The calculation of area amounts to expressing the length and the width in the unit desired for the final answer and simply multiplying the two numbers. We were introduced to this convenience of decimals in Sect. 1.2.

There is an inconvenience of decimal divisions, though, in common operations of simple commerce, where a commodity might have to be divided in half or in thirds or in quarters. Division of a decimal unit by three results in repeating decimals, and every division by two requires an additional decimal place. A dozen (or a 12-inch foot or a 12-oz troy pound) can be divided into halves, thirds, and quarters easily. It is not difficult to imagine accountants preferring decimals but salespeople preferring duodecimal divisions.[1]

Alder did more than point out why some aspects of the reforms left people dissatisfied; he also argues that the old measures fit some aspects of economic activity, in particular labor: "Indeed the whole thrust of the metric reform was to replace an economic system based on value, with one in which everything—human labor, as

[1] In fact, a system that combines the notational and computational ease of decimals with the richness in divisors of dozens was at least broached to the Académie and in the Committee of Public Instruction in the early 1790s [3]. This would involve base twelve arithmetic, in which the numbers zero through eleven would be represented by single digits, for example 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, χ and ε. Beyond single digits, the leading digit in a two-digit number represents twelves place, just as that digit in our familiar base ten system is tens place; thus twelve is represented by 10. The leading digit in a three-digit number represents twelve squared, in a four digit number, twelve cubed, just as in base ten they represent ten squared (a hundred) and ten cubed (a thousand) respectively. Fractions would be represented by places to the right of a divider—called a dozenal point rather than a decimal point. The first place to the right represents twelfths, the next 1/(twelve squared), etc.

well as its artifacts—was translated into the single, paramount variable of price" [3]. For example, land in some localities was harder to clear than in others, so the area of land that could be cleared in a day's work was different. Under this analysis, even uniformity using familiar families of units (for example, imposing Parisian units nationwide) would have met with resistance.

The Consulate (as the French government of the time was called) did not take long to countenance "translations" of the names of the new units. An order on the implementation of the new system of weights and measures issued in November 1800 (11 months after the law on the definitive standards) had two main provisions. It would make the new system mandatory throughout the country the following year, on the first day of year X (known as September 1801 elsewhere in the world), and it would permit the new units to be called by old familiar names in public acts. Thus, for example, a kilogram could be called a pound, a hectogram an ounce; a kilometer a mile, a centimeter a finger, and a millimeter a line [5]. Certainly the names of the units would be familiar. The effect of the law—to the extent that it was followed—would have been to change the values of many familiar units. A pound would weigh about twice as much, a mile would shrink to 5/8 of its former size.

The retreat from ill-received rational decimal systems continued over the next decade. As noted in the previous chapter, a concordat with the Roman Catholic church permitted the lapse of the 10-day *décade* in 1802, and France returned to the Gregorian calendar on 1 January 1806. Early in 1812, a decree countenanced a near total retreat from metric units. The decree begins "There will be no change to the units of weights and measures of the empire." But it goes on to approve multiples and divisions of those units that would best meet the needs of the people, and it calls on the ministry of the interior to make available instruments that read in both the legal (metric) measures and older customary measures [6]. In 1816, after the second restoration of the monarchy, the metric system was abolished for everyday business. Not until the 1830s did the system seem like a good idea again, and it was once again the compulsory system of weights and measures beginning in 1840 [3]. In July 1837, a law was passed permitting metric units with non-decimal divisions (something along the lines of the 1812 law) until 1 January 1840. On that date, the decimal metric system as spelled out in 1795 and 1799 would become the only legal system of weights and measures [7].

This time a commemorative medal (Fig. 3.1) *was* struck. The medallion called for in 1799 was never made, although the *Institut de France* specified the iconography at the time: the obverse would show an allegorical figure representing the French republic, standing on a 5-cm plinth, holding a decimally divided meter standard in one hand and a kilogram in the other; the reverse would feature a globe spanned from pole to equator by the points of an open compass [8].

Fig. 3.1 Medallion commemorating the invention and readoption of the metric system in France, 1840

3.2 Metrication Beyond France, 1851–1875

Few nations outside France adopted the metric system in the first half of the nineteenth century. The first spread was with Napoleon's armies, and some occupied nations readopted the system fairly quickly after the fall of the Empire [9]. The United Kingdom of the Netherlands, which encompassed Belgium and Luxemburg as well as the present-day Netherlands, was the first adopter outside France [10]. Portugal adopted a slightly disguised metric system in the 1810s, taking 1/10 m as its length unit and adopting names of Portuguese customary units rather than the French nomenclature [11]. Only the Kingdom of Sardinia (also known as Piedmont-Sardinia) and nominally Spain followed voluntarily before mid-century [9]. The qualifier "voluntary" excludes imposition of the system by a colonial power on its colonies.[2] France had exported the metric system to its colonies in Algeria and Senegal in 1840. Hector Vera notes that the role of colonialism has often been overlooked in studies of metrication. He writes that both colonialism and decolonization played significant roles in spreading the metric system around the world: former colonies into which the metric system had been introduced invariably retained it upon independence, while others (principally former British colonies) often adopted it upon independence [10].

The 1850s and 1860s saw the first voluntary adoptions of the metric system outside Europe. Nine Latin American nations made the metric system their official measures, beginning with New Granada (now Colombia) in 1853, followed over the next 15 years by Mexico, Venezuela, Brazil, Peru, Uruguay, Chile, Ecuador, the Dominican Republic and (in 1868) Bolivia. Vera notes that this large group of

[2] In the context of this chapter, voluntary refers to a free choice of a sovereign government in contrast to a colonial or other occupying force. In the context of Chap. 6, voluntary refers to the free choice of a business or other user of measures in contrast to legal compulsion imposed by the sovereign government in which the business operates.

adopters, often ignored in studies of metrication, for the most part wished to imitate European nations, but often preceded them [10].

Back in Europe, the Great Exhibition of 1851 in London was an important spur to interest in the system. The exhibition brought a great variety of goods into close proximity in a place where large numbers of scientists, statisticians, engineers, manufacturers and others could see them and notice the international diversity of measures in which they were denominated. This was particularly inconvenient for judges of various types of exhibits. The French display included a set of metric standards exhibited by the *Conservatoire des Arts et Métiers*—a potential solution to the babel of measures. Metric advocates sprang up in many nations in the next few years. The international exposition in Paris in 1855 had similar effects [9].

The International Statistical Congress advocated for metric units over the next decade. The first Congress, meeting in Brussels in 1853, urged governments reporting figures to include conversions to metric units. By 1860, the Congress voted for its members to urge adoption of the metric system in their own nations. Advocates for international uniformity in weights and measures formed an international association in the mid-1850s, soon establishing branches in 15 countries. Before the end of the decade, that association was urging adoption of the metric system [9].

The British branch of the association lobbied for adoption of the metric system, and in 1863 the British Association for the Advancement of Science joined it. The House of Commons passed a metric bill in 1863, too late to be acted on by the House of Lords. It looked as though the UK, the world's leader in trade and industry, was soon to adopt the system, and that in itself encouraged other nations to do the same [9]. The following year the UK passed a law legally permitting the metric system in contracts, but not in ordinary commerce [12].

Not all of the British scientific establishment favored the metric system. In 1863, Sir John Herschel (1792–1871) suggested that if a system of measures was to be adopted internationally for the promotion of trade, it ought to be the British imperial system, which was already more widely diffused. The Astronomer Royal of Scotland, Charles Piazzi Smyth (1819–1900) was the most prominent (but not the only) proponent of the idea that the Great Pyramid was a divinely inspired standard of measure at the root of British customary measures [13]. Movement of the British toward adopting the metric system was effectively derailed after a Standards Committee issued its second report on the matter in 1869. It found that the nation was not ready for such a conversion and that the superiority of metric to imperial units had not been demonstrated [9].

The metric system was also under consideration in the other large English speaking nation, the United States. Its National Academy of Sciences (founded in 1863) studied weights and measures and recommended the metric system in 1866. Later that year a law was passed that permitted, but did not require, use of the metric system in legal transactions [9]. (Metrication in the US is the subject of Chap. 6.) Two newly unified European nations adopted the metric system in the 1860s, as signs of national uniformity. These were Italy in 1861 and Germany in 1868 [10].

Interest in internationally uniform weights and measures was manifested in several events of 1867. That year's "Universal Exposition" in Paris had an exhibition on weights, measures and currency, including displays from around the world—not just around Europe. Among the exhibitors were Brazil, China, Egypt, Japan, Morocco, Turkey, the US and several other (unspecified) African, Asian and South American states [14]. Its pavilion was in the center of the grounds, inscribed with the words "Omnia, o Deus, fecisti ex numero, mensura et pondere" [15].[3] An international conference on the subject was held in conjunction with the exposition. Its delegates nearly unanimously declared that the metric system was best suited for use in industry, commerce and science [14].

Other international technical societies endorsed the metric system in 1867. The sixth International Statistical Congress called for its members in non-metric countries to form associations to lobby for metrication. The new International Geodetic Association endorsed the metric system for use in geodesy and called for an international commission to construct new metric standards [9]. Coming from an organization that grew out of a central European surveying project in which France had little involvement and Prussia much, this call prompted action in France to ensure that it would have a prominent role in any internationalization of the metric system [16].

In 1869 a committee of the French Académie des sciences reported to the full Académie its opinion that the meter and the kilogram were defined by the standards made in 1799 rather than by the abstract definitions that those standards were intended to embody. It proposed that the government invite other nations to form an international commission to decide how to make and disseminate copies of the standards to nations that wished to adopt the metric system [17].

The French government proceeded to invite other states in Europe and the Americas to appoint delegates to an International Commission of the Meter to meet in Paris in 1870. The Commission did meet on August 8–13, a few weeks after the start of the Franco-Prussian war. On the first day, some of the foreign members suggested (uncontroversially) that no firm decisions be made until the missing nations (Prussia and North German states) could be at the table. More controversially, they suggested that their job was to construct an international prototype of the meter, whereas they had been invited to work on making legal copies of the existing standard in the French Archives. They also wanted to expand the commission's scope to the entire metric system and to satisfy the needs of modern science. These goals were, after some discussion, adopted unanimously (including by a representative of the French government). The commission also agreed that the definition of the meter needed to be an artifact rather than a theoretical definition, whose experimental embodiment might be expected to change as science progressed [16].

The brief session of 1870 laid useful groundwork for the next meeting of the Commission in 1872. That meeting concerned itself with the kilogram as well as the meter. The question of whether to define the kilogram going forward on the theoretical definition of a cubic decimeter of water or the existing standard of the archives was debated and eventually resolved in favor of the artefact. The appeal of the theoretical definition was that it made the system connected, the weight standard

[3] "You have made everything, O God, from number, measure, and weight." See Wisdom 11:20—in some editions 11:21—in a Catholic Bible or a Protestant one that includes apocrypha.

depending on the length standard. Those who favored this connection recognized that defining the unit by the artefact was simpler and they were eventually convinced that the existing artefact embodied the desired relationship to sufficient accuracy. An alloy of platinum containing 10% iridium was selected as the material for making new standards of both units. The Commission also took some steps toward building longer-term institutions. It selected a Permanent Committee of 12 members, each from a different state. And it recommended founding an international bureau of weights and measures [16].

3.3 The Metre Convention of 1875 and the International Prototypes

Representatives of 20 states from Europe and the Americas met in Paris during spring 1875 at a conference that resulted in the Metre Convention. The participants included diplomats authorized to commit their countries, as well as special delegates versed in technical matters. The diplomatic conference appointed a special commission to resolve outstanding scientific matters before proceeding to government action. Jean-Baptiste Dumas (1800–1884), a highly respected chemist with some governmental experience, presided over the special commission [16]. Dumas had served on the Académie committee mentioned in the previous section tasked with considering the status of metric standards [17].

The treaty established institutions that continue to function today as custodians of the metric system and its expanded version, the International System of Units (*Système international d'unités*, SI). It established the International Bureau of Weights and Measures (*Bureau international des poids et mesures*, BIPM), sited near Paris, which would carry out metrological work involving the metric standards. The bureau was housed in France, but it was to function as an international body under the direction of an International Committee of Weights and Measures (*Comité international des poids et mesures*, CIPM). The CIPM itself operated under the authority of the General Conference of Weights and Measures (*Conférence générale des poids et mesures*, CGPM), comprised of representatives of the signatory nations, which would meet every few years [18]. The text of the treaty was signed initially in April 1875, and the CIPM was immediately constituted. The treaty was formally signed a few weeks later by 17 of the 20 nations represented at the conference (Table 3.1 lists the nations represented at the 1875 conference, the original signatories of the Metre Convention and the nations that had adopted the metric system by 1875.) The three nations at the conference that did not sign at the time were—in the order in which they subsequently joined the convention—the United Kingdom (1884), the Netherlands (1929) and Greece (2001). Among the original signatories was the United States. (Adhering to the Metre Convention does not imply adoption of the metric system, or vice versa; the Convention is about international institutions of standards and metrology.) The treaty has been modified since its adoption, but not since 1921 [16].

Table 3.1 International metric engagement in 1875

Attended 1875 metric conference [16]	Signed metre convention [16]	Adopted metric system [10]
Argentina	Argentina	Austria-Hungary
Austria-Hungary	Austria-Hungary	Belgium
Belgium	Belgium	Bolivia
Brazil	Brazil	Brazil
Denmark	Denmark	Chile
France	France	Colombia
Germany	Germany	Dominican Republic
Greece	Greece	Ecuador
Italy	Ottoman Empire	France
Netherlands	Peru	Germany
Ottoman Empire	Portugal	Italy
Peru	Russia	Liechtenstein
Portugal	Spain	Luxembourg
Russia	Sweden and Norway	Mexico
Spain	Switzerland	Monaco
Sweden and Norway	United States	Montenegro
Switzerland	Venezuela	Netherlands
United Kingdom		Ott
United States		oman Empire
Venezuela		Peru
		Portugal
		Romania
		Serbia
		Spain
		Sweden and Norway
		Switzerland
		Uruguay
		Venezuela

The first CGPM met in September 1889, after a batch of standards for both the meter and the kilogram had been made and compared. International prototypes were selected from among them, thenceforth defining the meter and kilogram. Nations adhering to the Convention received their national prototypes [16].

One century after the calls for uniform weights and measures across France were delivered to the Estates general of 1789, the system invented in response to those calls was embodied by new standards under international governance. The metric system had taken root in many territories outside its place of birth, and it was favored by many transnational organizations.

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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- ($T = \times 10^{12}$) to pico- ($p = \times 10^{-12}$) [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].

[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,

[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

[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].

[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.

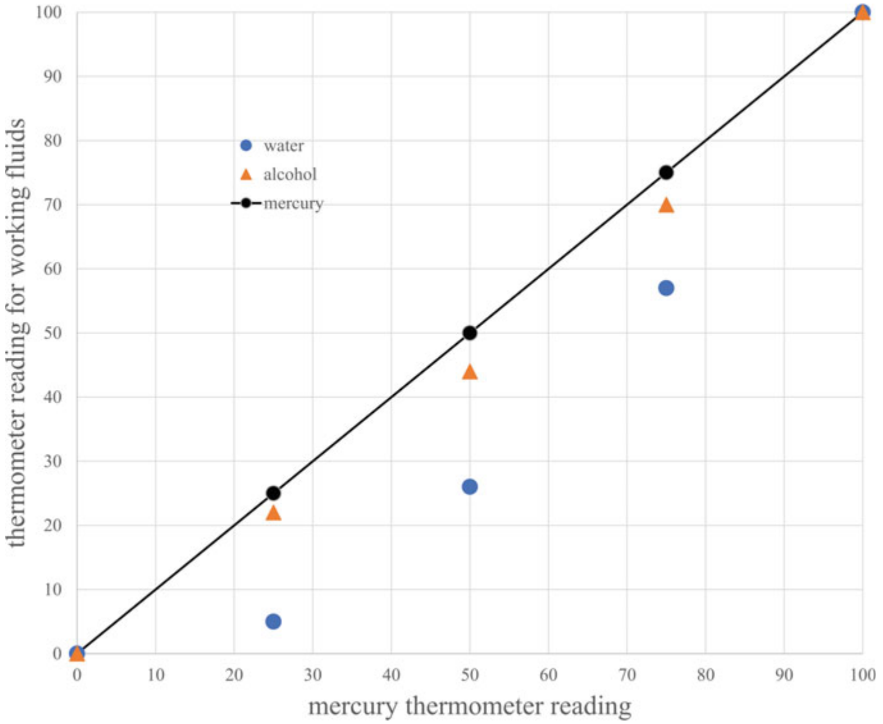

Fig. 4.1 Readings of thermometers based on various working fluids compared to the temperature read by a mercury thermometer (All three thermometers read 0 at the freezing point of water and 100 at the boiling point). Data given in Lamé 1836 [13]

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].

[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 $cm^{3/2}$ $g^{1/2}$ 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 $mm^{3/2}$ $mg^{1/2}$ 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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Chapter 5
Changes in the SI from Its Introduction (1960) to the Explicit-Constant Revision (2019)

Abstract After the introduction of the SI in 1960, some of the base units were redefined in terms of more stable standards or more precise measurement techniques. The biggest change in the system in its early years, though, was the addition of a seventh base unit, the mole, by the 14th CGPM (*Conférence générale des poids et mesures*, or General Conference of Weights and Measures) in 1971. A thorough revision of the SI was approved by the 26th CGPM in 2018, taking effect in 2019. The revision expressed all of the SI base units by fixing the values of such fundamental constants of nature as the speed of light and the Planck constant, resulting in today's explicit-constant SI.

5.1 The Mole, a Seventh Base Unit

The mole entered the SI as its seventh base unit by decision of the 14th CGPM in 1971 and upon advice of the International Union of Pure and Applied Chemistry (IUPAC), the International Union of Pure and Applied Physics (IUPAP) and the International Organization for Standardization (ISO). The definition of the mole adopted at that time specified it as the SI base unit of the quantity "amount of substance." A mole contained as many elementary entities as there were atoms in exactly 0.012 kg of carbon 12. Proper use of the unit mole included specifying the elementary entity (for example, electrons, chlorine atoms, fluoride ions, etc.) [1].

Chemists had been using the mole by name for several decades and had used the concept for a century or more. Before the term mole was coined, the terms gramme molecule and gramme atom were used. As Alexander Crum Brown explained in the 1878 edition of the *Encyclopedia Britannica* [2],

> For the sake of precision we sometimes speak of a molecule of water (or other substance) in grammes, or even of a *gramme-molecule, a grain-molecule*, etc. [italics in original] ... our gramme-molecule would then be a definite, very large, but not yet accurately ascertained, number of real molecules.

This explanation in an encyclopedia entry suggests that the usage was already common among chemists.

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The term mole or mol is frequently attributed to Wilhelm Ostwald (1853–1932) around 1900. The earliest use I found dates to an 1893 book by Ostwald, who defined a Mol as a gram molecular weight. He used the mole in the context of ideal gas behavior as well as in the optical rotation and electrical conductivity of solutions [3]. Georg Helm used the term in another book the following year, crediting it to Ostwald. Helm and Ostwald were skeptical of the reality of molecules, and Helm notes that the term Mol, unlike gram molecule, does not prejudge the question of the existence of molecules [4]. Mole also has the advantage of applicability to a wide range of chemical entities unlike the more specific (as well as more awkward) terms gram molecule and gram atom.

A gram molecule was the amount of a pure substance whose mass in grams was equal to the molecular weight of the substance. So what is a molecular weight or an atomic weight? Atomic weights (and the molecular weights based on them) initially formed a relative mass scale dating back to the work of John Dalton (1766–1844) in the early nineteenth century in his *New System of Chemical Philosophy* [5] and other publications. Over the next five or six decades determination of relative weights and formulas of chemical elements and compounds was a major research activity in chemistry. Readers interested in further information about these developments are referred to Alan Rocke's classic history *Chemical Atomism in the Nineteenth Century from Dalton to Cannizzaro* [6].

Dalton's scale was explicitly relative, and he chose hydrogen = 1 as his reference value [5]. Other researchers made other choices. Early on, the most common reference element other than hydrogen was oxygen. Jöns Jacob Berzelius (1779–1848) based scales on oxygen, including one with oxygen = 100 and one in which oxygen = 16 [6]. The latter resulted in atomic weights that were slightly but reproducibly different from those with hydrogen = 1. In 1899 an international commission on atomic weights was constituted, one which continues today as the Commission on Isotopic Abundances and Atomic Weights within IUPAC [7]. In its early years both O = 16 and H = 1 had their advocates. In fact, the 1903 international table of atomic weights included a column of values under each reference element [8]. Not long afterwards, though, the O = 16 scale became standard. After oxygen was discovered to have stable isotopes of mass number 17 and 18 in addition to the far more abundant oxygen 16, the scales used by physicists and chemists diverged slightly. Physicists made $^{16}O = 16$ while chemists continued to use the naturally occurring mixture of oxygen isotopes as their standard. By 1940 the natural proportions of oxygen isotopes were well enough established that a fixed factor of 1.000275 could be used to convert between the physical and chemical scales. The desirability of having a single atomic weight scale led to the international unions of both chemistry and physics agreeing (IUPAC in 1959, IUPAP in 1960) to a new unified atomic weight scale in which $^{12}C = 12$ [9].

In effect, these changes in atomic weight scale implied changes in the definition of the widely used but not officially defined mole or gram molecule. Recall that Brown's encyclopedia entry recognized that a gram molecule contains a definite number of molecules. An atomic weight scale based on H = 1 implies that a mole contains as many elementary entities as there are atoms in exactly 1 g of hydrogen. Similarly the O = 16 scale implies that a mole contains as many entities as there are atoms in exactly 16 g of oxygen. The $^{12}C = 12$ implies that a mole contains as many entities as there are atoms in exactly 12 g of carbon 12. This last definition is equivalent to the formal definition of mole adopted by the CGPM in 1971.

Having defined the mole as a unit of measure, the question arises "What physical quantity does the mole measure?" The official name of the corresponding quantity in English is "amount of substance." The IUPAC Green Book notes [10]

> The quantity "amount of substance" or "chemical amount" … has been used by chemists for a long time without a proper name. It was simply referred to as the "number of moles." This practice should be abandoned, because it is wrong to confuse the name of a physical quantity with the name of a unit.

Yet more than a generation after the inclusion of the mole in the SI as a unit of "amount of substance," the phrase "number of moles" continued to appear in many more peer-reviewed chemistry papers than the phrase "amount of substance"—at least if American Chemical Society (ACS) publications are representative. The "mole concept" is a perennial subject in the *Journal of Chemical Education*, some articles emphasizing the mass aspect of the unit, some the number, and some pointing to "amount of substance" as if that term clarified the matter [11].

It is interesting to speculate on whether chemists would have proposed a term that would have been more widely accepted than "amount of substance" if the need for a name of the quantity had arisen earlier, before the mole was practically the only unit employed to measure the quantity. Brown's encyclopedia entry mentioned gramme-molecule, grain-molecule and ton-molecule [2]. What if the need to have a formal name distinct from the unit had been posed at that time to an international committee on nomenclature and units? As it is, the desirability of an alternative name has been recognized by official bodies such as IUPAC. Chemical amount has quite a bit of support as an alternative [12]. In my opinion, chemical amount is more specific and therefore better than amount of substance, but it is not specific enough, particularly in the context of a chemistry course in which amounts can be directly measured, for chemical purposes, in mass or volume units. My own suggested term is stoichiometric amount [13].

At least one more question arises from the 1971 definition of the mole: how many atoms of ^{12}C ***are*** there in 12 g of ^{12}C? Before we answer the question, note that knowing the answer is not necessary for most practical uses of amount of substance: that quantity is rarely used to determine numbers of elementary entities, and numbers of entities are rarely used to determine chemical amount.

The conversion factor between the unit mole and the number of entities a mole contains is called the Avogadro constant, N_A. Among chemists, the number of entities in a mole is known as Avogadro's number (sometimes also symbolized as N_A). The difference is that the constant has units of mol^{-1} while the number is a pure number (that is, dimensionless). When the mole entered the SI, the best estimate of the Avogadro constant was in the range between 6.0221×10^{23} mol^{-1} and 6.0225×10^{23} mol^{-1} [14].

The constant is named after the nineteenth-century Piedmontese natural philosopher Amedeo Avogadro (1776–1856). Avogadro discovered that equal volumes of different gases under the same physical conditions of temperature and pressure contain equal numbers of molecules. What that number was, he had no idea. The constant was named for Avogadro by French physicist Jean Perrin (1870–1942) in 1909 [15, 16], but estimates of its value predate those of Perrin and his naming it.

Johann Josef Loschmidt (1821–1895) was a high-school teacher when he published a paper on the size of molecules in air. With an estimate of a molecular diameter in hand, Loschmidt could have computed the number of molecules in a given quantity of matter, but his molecular size paper did not do so. However, a summary of that paper which appeared in another journal later in 1865 included an estimate of 866×10^{12} molecules mm^{-3}. This number does not follow from Loschmidt's calculations, though, and it is not clear whether the summary was by Loschmidt or an anonymous abstractor [17].

In the first years of the twentieth century, two giants of modern physics did theoretical work that connected the microscopic and macroscopic realms, providing ways of estimating the number of microscopic entities in a gram atom or gram molecule. In 1901 Max Planck (1858–1947) combined statistical mechanical arguments with values of constants derivable from radiation laws, arriving at the theoretical result that the ratio of the Boltzmann constant to the ideal gas constant is the same as the ratio of the mass of an atom to the mass of a gram-atom. He reported that a single molecule is 1.62×10^{-24} of a gram molecule [18, 19]. This amounts to 6.17×10^{23} for the (still unnamed) Avogadro's number. In 1905 Albert Einstein (1879–1955) published an article on Brownian movement, a phenomenon involving suspensions of small but optically detectable colloidal particles buffeted by smaller and invisible molecules. Near the end of that paper he presented an equation that related Avogadro's number to the mean displacement of such particles and measurable quantities such as viscosity. He returned to Brownian movement later in 1905, writing a paper on molecular dimensions that appeared the following year, with corrections published in 1911. His estimate for Avogadro's number was initially 3.3×10^{23}, changed to 6.56×10^{23} based on the corrected analysis [20].

Perrin was among the experimenters who took up Einstein's theory of Brownian movement. In the paper in which he coined the term "Avogadro's constant," he also reported his determination of Avogadro's number[1] on the basis of the height distribution of particles in a colloidal suspension under the influence of gravity, namely 70.5×10^{22} [15, 16].

Perrin marshaled all sorts of evidence for the particulate nature of matter in his 1913 monograph *Les Atomes* [21, 22], in the process giving values of Avogadro's number from many different lines of evidence. He adopted the value 68.5×10^{22} for Avogadro's number from Brownian movement (p 124[2]). Perrin reported estimates of the number based on entirely different phenomena as well. It could be obtained from

[1] Perrin's phrase was *constante d'Avogadro*, but I will report his (dimensionless) estimates as Avogadro's number, making the distinction between the terms that arose after his time.

[2] Page numbers in this paragraph refer to the English translation [22].

measurements of critical opalescence via analyses by Smoluchowski and Keesom; measurements on ethylene led to 75 $\times$ 10^{22} (p 138). Avogadro's number could be inferred (at least to the correct order of magnitude) from measurements of Rayleigh scattering of visible light in the atmosphere (p 141). One could fit data on black-body spectral distributions to determine the Planck constant and Avogadro's number simultaneously; the latter was 64 $\times$ 10^{22} (p 153). Counting radioactive α decays and measuring the electric **charge** deposited by such decays were also used to find the elementary charge and then Avogadro's number; data on radium from Ernest Rutherford (1871–1937) yielded 62 $\times$ 10^{22} (p 201). Comparing the rate of helium production from decay of radium to the number of decay events also allowed the constant to be computed; 65 $\times$ 10^{22} was reported (p 202). The decay kinetics of radium was used to find Avogadro's number by comparing the rate of discrete decay events to the fractional decay rate to find the number of atoms in a mole of radium, namely 75 $\times$ 10^{22} (p 203). The energetics of radium decay also yielded the number by combining rates of heat generation with branching ratios and kinetic energies of captured α particles: 60 $\times$ 10^{22} (p 204). Measurements of the charge of the "atom of electricity" permitted estimation of the number via comparison to the Faraday constant obtainable from electrolysis. The discontinuous nature of electricity was demonstrated by observing tiny droplets or particles of dust or smoke under ionizing conditions. Perrin cited work published by Robert Millikan (1868–1953) in 1911 (before what is now considered his definitive work on the subject), obtaining an estimate of 59 $\times$ 10^{22}; measurements by Perrin's doctoral student Jules Roux, attempting to replicate Millikan's work, led to an estimate of 69 $\times$ 10^{22}.

Millikan is best known today for measurement of the electron charge by means of his famous oil-drop experiment. He was well aware of the fact that combination of this microscopic electrical constant, e, with the macroscopic Faraday constant, F, yields the Avogadro constant. Indeed, the title of his classic 1913 paper is, "On the Elementary Electrical Charge *and the Avogadro Constant*" (my emphasis) [23]. The experiments reported in *this* paper represent improvements over his previous work undertaken in order to determine the constants with greater accuracy and precision. In effect, Millikan's emphasis was no longer on simply attempting to assess the magnitude of the constants, but on determining their precise values. His best estimate of Avogadro's number, including uncertainties was $(6.062 \pm 0.012) \times 10^{23}$.

Indeed, precision really was the point of measurements of Avogadro's number from then on. A review of such measurements from the early 1930s notes that the variety of methods that agree to the first figure or two is impressive, but that very few methods could give the third figure with reasonable precision or accuracy. The main contenders were the balanced drop measurements of electron charge by Millikan and replicated by others, a statistical fit of determinations of the Planck constant and electron charge, and precise measurements of X-ray wavelengths [24]. At the end of the 1920s, the balanced drop measurements appeared to give the best results, but statistical data analysis and X-ray measurements have been at the forefront ever since.

In 1925, Arthur Compton (1892–1962) and Richard Doan recorded X-rays reflected from a ruled diffraction grating, noting that such measurements permit determination of X-ray wavelengths to high precision [25]. The technique of X-ray crystal diffraction (XRCD) has been used to determine the value of the Avogadro constant essentially by comparing a macroscopic volume (obtained from density measurements) to the volume of a microscopic unit cell obtained from diffraction of X-rays of known wavelength. Before Compton and Doan, though, X-ray wavelengths were more uncertain than Avogadro's number, and those wavelengths were computed from lattice parameters determined from the crystal density, the molar mass, and the Avogadro constant. In effect, Compton and Doan enabled XRCD measurements of the Avogadro constant.

Throughout the 1930s the source of a small but persistent difference between values derived from XRCD and from the oil drop experiment was much debated. Eventually, the discrepancy was traced to a systematic error of about 0.4% in the viscosity of air, a quantity that entered into oil-drop experiments, making Millikan's value for the electron charge too small by about 0.6% (and his value of the Avogadro constant too large by the same relative amount). In the middle 1940s, Raymond Birge reviewed X-ray based determinations of the Avogadro constant based on diffraction experiments using several crystals: calcite, sodium chloride, diamond, lithium fluoride, and potassium chloride. The values agreed to four figures [26].

Meanwhile statistical data analysis was also brought to bear on the constant. Several mathematical relationships link physical constants such that independent measurements of various constants constitute an overdetermined system of equations. Finding the optimal values of the constants can be accomplished by statistical methods such as least squares analysis. Birge and W. N. Bond pioneered critical evaluation and statistical methods to the problem of simultaneous determination of many physical constants [26].

5.2 Incremental Changes in the Base Units

The addition of a seventh base unit to the SI was not the first change made to the system after its establishment by the 11th CGPM in 1960. The only change made by the 12th CGPM in 1964 was the addition of two more SI prefixes for smaller divisions, namely femto - (f = $\times$ 10^{-15}) and atto - (a = $\times$ 10^{-18}) [1].

The 13th CGPM in 1967 and 1968, however, changed the definitions of three base units—one radically and two slightly. The definition of the second was detached from astronomy and tied to the frequency of an atomic transition: "The second is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom" [1]. Thus the second became the next SI base unit (after the meter) defined in terms of fixed atomic constants along the lines envisioned nearly a century earlier by James Clerk Maxwell (Sect. 4.1). Redefinition of the second is on the agenda of the CGPM again in the 2020s, as optical frequency sources have already surpassed the precision possible to obtain from the caesium hyperfine transition. In addition, the CGPM is reexamining the continued use and frequency of leap seconds that keep Universal

Coordinated Time (UTC, *Temps universel coordonné*) synchronized with the earth's motion [27]. Recall that leap seconds interrupt the smooth operation of high-precision timekeeping.

The name and the definition of the unit of thermodynamic temperature changed slightly. The word degree and symbol ° were dropped: the unit was no longer the degree Kelvin (°K) but the kelvin (K). The definition was altered slightly to define the unit explicitly as 1/273.16 of the thermodynamic temperature of the triple point of water [1]. Ignoring for the moment the slight change in the unit's name, this definition is formally equivalent to the previous definition that set the triple point of water at 273.16 K. The difference is one of emphasis: the former definition said how many units made up a given fixed temperature, whereas the revised definition said explicitly what fraction of a given fixed temperature was the temperature unit. Klein observes that this rewording makes the status of the kelvin as a true unit (as opposed to an arbitrary scale) more clear [28]. The everyday experience of most people with temperature, in the contexts of weather and cooking, is with arbitrary scales rather than units. A hot summer day of 30 °C is in no physical sense twice as hot as a spring day of 15 °C. Nor is a pizza baked at 450 °F more than twice as hot as boiling water at 212 °F.

The other definition of a base unit revised by the 13th CGPM was that of the candela, the luminous intensity perpendicular to a surface of 1/600,000 m^2 of a blackbody at the temperature at which platinum freezes at a pressure of 101,325 N m^{-2} [1]. Again, the definition was made explicit for the unit, stating what one candela was rather than how many candelas were emitted from a surface of a particular size. This definition also clarified intensity normal (perpendicular) to the emitting surface. By specifying the pressure (standard atmospheric pressure), the definition made explicit that the reference temperature was the standard freezing temperature of platinum. The alternative name for the unit, new candle, was abrogated.

The next (14th) CGPM saw the addition of the mole to the SI, discussed at length in Sect. 5.1. The 15th CGPM added two SI prefixes at the large end of the scale, peta - ($P = \times 10^{15}$) and exa - ($E = \times 10^{18}$). The 19th CGPM (1991) added four more prefixes, two matching pairs: zepto - ($z = \times 10^{-21}$) and zetta - ($Z = \times 10^{21}$), yocto - ($y = \times 10^{-24}$) and yotta ($Y = \times 10^{24}$). These last names were chosen to echo Greek roots for seven and eight, alluding to the seventh and eighth powers of 10^3 [1]. Thus these pairs were deliberately chosen to look and sound similar; presumably the context would help avoid confusion. The range of SI prefixes was extended still further by the 27th CGPM in November 2022 to include the new prefixes ronto - ($r = \times 10^{-27}$) and ronna—($R = \times 10^{27}$) as well as quecto - ($q = \times 10^{-30}$) and quetta - ($Q = \times 10^{30}$) [27].

The candela was redefined again in 1979. Realizations of the previous definition proved problematic. The Consultative Committee for Photometry and Radiometry advocated a change from properties of a luminous source to those of a radiometric detector, taking into account the response of the human eye. In fact, it proposed to change the photometric base unit from the candela, a unit of luminous intensity (source-based) to the lumen, a unit of luminous flux (receptor-based). The CIPM (*Comité international des poids et mesures*, International Committee of Weights and

Measures) and CGPM did not want to change base units, though. So the 16th CGPM adopted a new definition of the candela based on the energy of a monochromatic light, selected for sensitivity of the human eye to it [29]. It made the candela the luminous intensity of a monochromatic light source of frequency 540×10^{12} Hz (wavelength 556 nm) whose radiant intensity was 1/683 W per steradian [1].[3]

The 17th CGPM in 1983 changed the definition of the meter by fixing the value of the speed of light in vacuum, *c*. This quantity had been measured with great precision, and it was of fundamental importance in several branches of physics. It would be convenient for some of those branches if *c* had an exact value. And giving *c* an exact value corresponding to its best-estimate previously determined experimental value, permitted the meter to be defined more precisely than before. The new definition set the meter as the distance that light travels in vacuum in 1/299,792,458 of a second [1]. This was the first SI base unit to be defined in terms of a fundamental constant of nature. To be sure, the previous definition of the meter was also based on a constant (invariant) of nature. Properties such as wavelengths and frequencies of specific transitions in specific atoms are constants of nature, and the previous definition of the meter and (still) current definition of the second are based on such constants. Fundamental constants, though, are not tied to particular substances and are of more general importance in physics. Fundamental constants include the electron charge *e* and the Planck constant *h* encountered in Sect. 5.1, as well as *c*.

5.3 The Explicit-Constant SI

Not many years after the meter was redefined in terms of the speed of light, a proposal was made to CIPM to redefine the kilogram in terms of the Planck constant or the Avogadro constant. The proposal came in the form of a paper by five well-established metrologists published in 2005 titled "Redefinition of the Kilogram: A Decision Whose Time Has Come" [30]. One of the paper's authors, Terry Quinn, then recently retired as director of BIPM (*Bureau international des poids et mesures*, or International Bureau of Weights and Measures), described the title as "slightly provocative" [29]. (To me it appears needlessly inauspicious, echoing the US Metric Study's 1971 report to the US Congress "A Metric America: A Decision Whose Time Has Come." See Sect. 6.2 for more on that report.) Quinn describes the response to the proposal as negative at BIPM, among metrologists of mass and elsewhere. Yet by the time of the 24th CGPM in 2011, that proposal had been extended, and CIPM had embraced it. CGPM also endorsed it, encouraging national metrological institutes and other organizations to work together to carry out the experiments and other work necessary to accomplish it [29]. In fact the 26th CGPM in 2018 approved a major revision of the SI that took effect in 2019 [1].

The 2005 proposal noted that the kilogram was the only base unit of the SI embodied by an artifact subject to wear and damage and unconnected to any constant

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[3] A steradian is a measure of solid angle.

of nature. Any uncertainty in the kilogram applied to the mole (whose definition included the kilogram explicitly) as well as the ampere and candela (whose definitions included the kilogram implicitly through units of force and power). If the kilogram could be redefined in terms of a constant in such a way that did not increase the relative uncertainty inherent in mass measurements under the then-current definition, then not only would the unit be tied to a constant, but also that constant would be fixed with zero uncertainty. Two technologies appeared promising in reducing the uncertainty in measured values of the relevant constants to the point where one of them could be fixed. One was the watt balance, now called the Kibble balance in honor of its inventor, Bryan Kibble (1938–2016). This instrument is based on an equal-arm balance, one of whose arms measures gravitational force (i.e., weight) and the other electromagnetic force. It can be used to obtain precise determinations of the Planck constant. The other is XRCD to determine the Avogadro constant. Techniques for fabricating large silicon crystals of exceptional purity permitted the application of XRCD to silicon to yield very precise determinations of the Avogadro constant [30].

The 2005 proposal may have met with opposition at the time, but parts of the proposal were already three decades old. Work by Richard Deslattes and co-workers at the US National Bureau of Standards made something of a splash in the 1973 CODATA report of the best-estimate values for physical constants. CODATA is the Committee on Data of the International Science Council. Founded in 1966, it began publishing authoritative best estimates of the values of physical constants every few years beginning in the 1970s. In the body of the 1973 CODATA paper, work by Deslattes and William Sauder was mentioned but not included in the data analysis because it was too preliminary. In a note added in proof, however, later results by Deslattes and Albert Henins were described as so reliable and precise as to make earlier X-ray measurements obsolete. This work used optical and X-ray interferometry to determine the wavelength of X-ray lines with much greater precision, and it obtained a value of the Avogadro constant by XRCD on single-crystal silicon [31]. A year later one could read informed speculations such as, "… with further refinements of these techniques, it may be possible to redefine the kilogram in terms of the product of the Avogadro constant and 1/12 the mass of a carbon-12 atom. This definition would remove the last remaining artifact standard …" [32].

By 2011, the plan to revise the SI was well underway. The plan was to redefine the kilogram in terms of the Planck constant and not in terms of the Avogadro constant or the mass of a nuclide. The Avogadro constant would be used as the basis of a redefinition of the mole. The ampere would be redefined in terms of the fundamental electric charge e, and the kelvin in terms of the Boltzmann constant k. Furthermore, the definitions of all seven SI base units would be formulated in explicit-constant rather than explicit-unit terms [29]. It would take a few more years before experimental determinations of the Planck and Avogadro constants yielded results that were sufficiently precise and consistent to make the redefinitions continuous with the values and precisions of the units then in force. The new definitions were finalized in 2017 [33] and adopted at the 26th CGPM in 2018 to go into effect in

2019 [1]. The new logo of the SI (Fig. 5.1) displays the abbreviations of the seven base units and the seven constants that define them. Table 5.1 gives the fixed values of the defining constants and the units they define.

Perhaps the best way to illustrate the difference between explicit-unit and explicit-constant formulations is by example. Consider the explicit-unit definition of the meter adopted in 1983, namely the distance that light travels in vacuum in 1/299,792,458 of a second, and the explicit-constant definition that replaced it: the meter is "defined by taking the fixed numerical value of the speed of light in vacuum *c* to be 299,792,458

Fig. 5.1 Logo for the revised International System (SI) of units. Used with permission of the Bureau International de Poids et Mesures (BIPM) under a Creative Commons Attribution-NoDerivatives 4.0 International license (https://creativecommons.org/licenses/by-nd/4.0/)

Table 5.1 The seven base units of the revised SI along with their defining constants [1]

Unit	Quantity	Constant	Value
Second, s	Time	Frequency of caesium hyperfine transition, $\Delta\nu_{Cs}$	9,192,631,770 s^{-1}
Meter, m	Length	Speed of light, *c*	299,792,458 m s^{-1}
Kilogram, kg	Mass	Planck constant, *h*	$6.62607015 \times 10^{-34}$ kg m^2 s^{-1}
Ampere, A	Electric current	Elementary charge, *e*	$1.602176634 \times 10^{-19}$ A s
Kelvin, K	Thermodynamic temperature	Boltzmann constant, *k*	1.380649×10^{-23} kg m^2 s^{-2} K^{-1}
Mole, mol	Amount of substance	Avogadro constant, N_A	$6.02214076 \times 10^{23}$ mol^{-1}
Candela, cd	Luminous intensity	Luminous efficacy of 540 THz radiation, K_{cd}	683 cd sr kg^{-1} m^{-2} s^3

when expressed in the unit m/s” (the second having already been defined) [1]. Obviously the two definitions are mathematically and conceptually equivalent; the difference is that the former explicitly states the value of the unit whereas the latter implies the value of the unit from the explicit value of the constant.

Among the definitions of the revised SI, one stands out as including both explicit-constant and explicit-unit aspects [1]:

> The mole, symbol mol, is the SI unit of amount of substance. One mole contains exactly $6.02214076 \times 10^{23}$ elementary entities. This number is the fixed numerical value of the Avogadro constant, N_A, when expressed in the unit mol^{-1} and is called the Avogadro number.

This definition explicitly says how many entities a mole contains (explicit unit) and the value of the Avogadro constant (explicit constant)—and as a bonus gives an official definition for the widely used term Avogadro number.[4] This explicit-unit formulation was a change from an explicit-constant definition previously drafted, made at the behest of IUPAC after wide consultation with its member organizations and despite the objections of some metrologists [33].

IUPAC’s consultations included both the definition of the mole and the name of the quantity amount of substance. Its findings were published in an extensive technical report [12]. Its final recommendation included no proposal to change the name amount of substance, but it noted “A thorough examination of a potential alternative name for the quantity amount of substance, *n*, has to be performed” [34].

For the vast majority of users of SI and metric units, including for most research scientists, the change in definitions has had no effect. That is largely by design: the values selected for the defining constants were chosen in order to provide continuity with the old definitions: to great precision—to a greater precision than all but the most precise measurements—both the units and the constants have the same values as before the revision. As a practical matter, standards for practical measurements have not changed either: a laboratory balance is still calibrated by comparison with a reference mass (usually a piece of metal) even if the mass unit is no longer defined in terms of a particular piece of metal. The revision requires some adjustment in science education, at least to the extent that the definitions of SI units are part of the content in science courses. The new definition of the mole is closer to the way that that unit was taught than the one it replaced [12]. On the other hand, the new definition of the kilogram, even when cast into an explicit-unit form, $1\ \text{kg} = (h/6.62607015 \times 10^{-34})\ \text{m}^{-2}\ \text{s}$, is highly abstract. It violates a prime pedagogical precept by defining a more familiar or more concrete concept in terms of a less familiar and more abstract one. This is not intended as a criticism of the definition of the kilogram, for an official definition of this sort must aim at precision, and it is not intended as a pedagogical statement. Rather, it is a statement of the challenge the new definition poses to those who must teach it [35].

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[4] “Avogadro’s number” is used more frequently than “Avogadro number”—or “Avogadro constant” or “Avogadro’s constant” for that matter.

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Chapter 6
The Metric System and the United States

Abstract The United States is famously the largest of a very few nations whose everyday weights and measures are not metric. Less well known are the facts that the US was among the signatories of the Metre Convention in 1875 or that the meter and the kilogram have been the fundamental standards of length and mass in the US since the late nineteenth century. The US and the metric system have had several episodes of approach and avoidance over the whole of the lifetime of that system. This chapter describes briefly the history of the status of the metric system in the US. At present the system is legal in the US and is used in some applications; however, customary units remain the weights and measures most commonly employed by most people in the US for everyday purposes.

6.1 Introduction: The Metric System in the US Today

Imagine preparing for a picnic at a park or a beach in the US reached after an hour's drive in an automobile. The fruits and vegetables bought from a local market are priced by the pound or by the ounce. Gasoline or diesel fuel for the car is dispensed in gallons. The weather forecast for pleasant conditions gives the temperature in degrees Fahrenheit. And the road signs on the way display distances in miles. Similar preparations elsewhere in the world would encounter food priced by the kilogram or perhaps hectogram, fuel measured in liters, temperatures reported in degrees Celsius[1] and distances denominated in kilometers.[2]

The US is in many ways a non-metric[3] island in a metric ocean. It is not the only island in the non-metric archipelago, but it is by far the largest of a very small number of countries. It is commonly stated in books and on the internet that the only nations that do not use the metric system are the US, Liberia and Myanmar. Hector

[1] Kelvins are not used for mass media meteorology; however, degrees Celsius are an SI unit, albeit not a base unit.

[2] Road signs in the United Kingdom still use miles.

[3] I use "non-metric" to describe nations like the US in which customary non-metric units predominate in everyday use. In the twenty-first century there are no countries that don't use the metric system, as discussed below, and the metric system ***is*** used in the US.

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Vera's extensive 2011 study of metrication added four small Oceanian countries to that list: the Marshall Islands, the Federated States of Micronesia, Palau and Samoa [1]. Samoa has since adopted a metrology act that recognizes mainly metric units for trade, but permits some US customary units for weight and volume alongside metric ones [2]. US influence is strong in the other three Oceanian countries. After World War II they were part of the Trust Territory of the Pacific Islands, administered by the US. Now they are sovereign states formally associated with the US through a Compact of Free Association [3].

Whereas Vera criticized the assertion that only the US, Liberia and Myanmar do not use the metric system on the grounds that the list was incomplete, Elizabeth Benham disagrees with the premise that there are any countries that do not use the metric system. Benham, Metric Coordinator at NIST (the US National Institute of Standards and Technology, successor of the National Bureau of Standards, NBS), notes that use of the metric system in any nation is best described along a continuum; a simple yes or no classification is inadequate and misleading. In the US, she notes, customary units such as miles, gallons and pounds are in clear evidence on the surface; however, uses of the metric system lie beneath the surface, like an iceberg, mainly out of sight (Fig. 6.1) [4]. Some of the metric industry practices alluded to in Fig. 6.1 are visible. For example, packaged household products and foods in the US are required to show both metric and US customary units on the label [5]. The bottle of dish soap under my sink reads 19 fl oz and 561 mL, and the package of pasta in my pantry says 1 lb (454 g). The nutrition labels on such foods list quantities of components such as fats or sodium in grams or milligrams—but energy content in non-metric calories and serving sizes in both customary and metric units. Other metric industry practices are less visible: many products are made using metric machinery or specifications. I would add scientific practices alongside industry practices: science in the US—and everywhere else in the world—uses metric units, as does science education. The base of the iceberg in Fig. 6.1 states that the SI is the foundation of the US measurement system. This is largely invisible to the public. US customary units are defined in terms of metric standards. NIST is the key federal government agency in the US measurement system, tasked with promoting industry and innovation in the US through measurement science. At the same time, it is among the world's leading metrology laboratories and in that capacity contributed substantially to the measurements involved in the explicit-constant SI described in Sect. 5.3.

6.2 Metric Conversion in the US: A Decision Whose Time Has not yet Come

As seen in Sect. 1.6, the young US considered a decimal system of weights and measures at around the same time that the metric system was being devised in the late eighteenth century. At that time the national government did not use its authority to set uniform weights and measures, so the customary measures based on the British

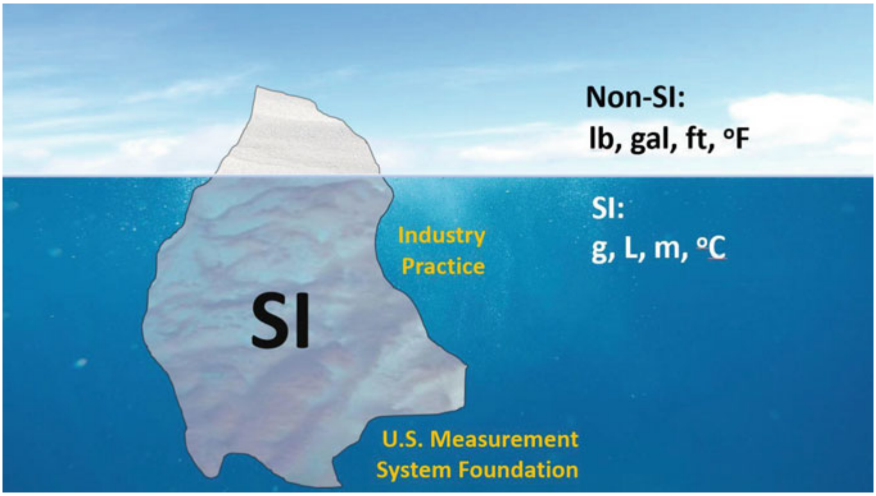

Fig. 6.1 US measurement infrastructure illustrated as an iceberg dependent on the SI. *Credit* Elizabeth Benham. Reprinted with permission courtesy of NIST. All rights reserved, US Secretary of Commerce

system continued in use under the regulation of the states. The US was not among the nations invited to participate in the conference that produced the first definitive meter and kilogram in 1799 (Sect. 2.7).

The next serious consideration of weights and measures by the US government came in the years just before and after 1820. In December 1816, near the end of his second term, President James Madison's annual message to Congress noted that no action had been taken to establish uniform weights and measures. Madison recommended the decimal system that had been proposed by Jefferson some 25 years earlier. The Senate quickly formed a committee. In 1817 it asked the Secretary of State, John Quincy Adams (1767–1848), to report on practices used in other countries on uniform weights and measures and on what practices might be beneficial for the US to adopt [6]; the House of Representatives made a similar resolution in December 1819 [7].

Adams's report, delivered in 1821, was thorough, treating foreign countries first, then regulations and standards in states of the US, and ending with proposals for the US. Adams was effusive in his praise of the metric system and of the basic science that came out of its invention [7]:

> This system approaches to the ideal perfection of *uniformity* applied to weights and measures; and, whether destined to succeed, or doomed to fail, will shed unfading glory upon the age in which it was conceived, and upon the nation by which its execution was attempted, and has been in part achieved.

Adams's comparison of the French and English systems reads like a comparison of the rational and the practical. Despite his admiration for the metric system, he is not sure that it is up to the task for which it was designed. In the end, Adams counsels no change in the nation's units. He doubts whether the authority given by the Constitution to Congress "to fix the standard of weights and measures" permits it to *change* "the denominations and proportions already existing." A conversion to the metric system would also be difficult to implement. Adams noted that weights and measures seemed to be on the agendas of several "populous and commercial nations," namely France, Great Britain, Spain and the US. An agreement among them would obviously be advantageous, and it ought to be explored. Meanwhile, though, the Congress ought to declare what were the legal weights and measures currently in force in the US and to have standards made and distributed to the states [7]. Not even these modest recommendations were implemented [6].

The first weight standard established by the US government was a copy of the British imperial troy pound. The Mint Act of 1828 established that standard for use in the US Mint in Philadelphia. Thus, the standard was fixed for a limited and particular purpose; nevertheless, the act appears to have been the first act of Congress that specified a weight or measure for any purpose. The standard had been acquired in 1827 by US Minister to London Albert Gallatin (1761–1849) explicitly for use by the Philadelphia Mint [6].

Not long afterwards Congress initiated a series of actions that led to a greater uniformity of weights and measures across a branch of the US government, namely its custom houses. In 1830 it passed a resolution directing the Secretary of the Treasury to make comparisons among the weights and measures used at the main custom houses of the US in order to ensure the proper collection of revenue. The task was delegated to Ferdinand Hassler (1770–1843), Superintendent of the Coast Survey. He reported that there was some variation among the standards used, but on average they reflected the English standards in use at the time of the American Revolution. Standard yards, avoirdupois pounds, gallons and bushels were then constructed and distributed to the custom houses. In 1836, Congress directed the Secretary of the Treasury to have complete sets of the custom-house measures sent to each state. Although the purpose behind the resolution was to promote uniformity in weights and measures, it did not explicitly fix these standards as national standards [6].

The US was not immune to the influences and incentives in favor of uniform weights and measures among commercial nations described in Chap. 3. Its products were on display at the London and Paris international expositions in the 1850s and 1860s—albeit at a reduced scale in the 1862 London exhibition during the Civil War.

In 1866, the National Academy of Sciences committee on weights and measures issued a report urging the US government "to authorize and encourage by law the introduction and use of the metrical system of weights and measures." Not included in the report, but communicated to the Secretary of the Treasury along with the report, was the minority opinion of the committee that it would be difficult for "a government like ours" to mandate such a change, and that if the US and UK worked out a system between them, it would quickly be adopted widely. Later that year, the US passed a law that made metric measures legal throughout the country. A bill that would have made the metric system mandatory after a transition period had been introduced but withdrawn. When the House Committee of Coinage, Weights and Measures reported on the permissive metric bill, it expressed a hope that it was only the first step of a reform that a later Congress would extend before too much longer [8].

When Congress legalized the metric system, it also directed the Secretary of the Treasury to have sets of metric standards fabricated and distributed to the states.[4] The Office of Weights and Measures had on hand standards of respectable provenance, known as the "Committee meter" and the "Arago kilogram," from which to make copies. The meter standard was an iron copy of the French meter of the archives made under the supervision of the international committee that produced the definitive metric standards in 1799. This copy was given by J.-G. Trallès, the commissioner from the Helvetian Republic (that is, Switzerland), to his friend Hassler. Hassler, mentioned above as the Superintendent of the US Coast Survey, was born in Switzerland. When he came to the US in 1805, he brought the meter bar with him [9]. A few years later, his fellow Swiss, Gallatin, then Secretary of the Treasury, introduced Hassler to President Jefferson, who appointed Hassler to oversee the new Coast Survey. Hassler resigned that post before the appropriate instruments could be made, but he regained it decades later in 1832 [10]. Gallatin was directly involved in procuring the "Arago kilogram" when he was US Minister to France. He obtained a platinum meter in addition to this platinum kilogram. Both of Gallatin's standards were compared to the French standards of the archives and certified by the French physicist François Arago [9].

Vera writes that 1866 was a propitious time for the US to adopt metric measurements for several reasons. Many nations have adopted the metric system during times of great upheaval or in their aftermath, and the recently concluded Civil War certainly fits that category. In addition, some of the caution expressed by Jefferson and Adams over being early adopters of a system that might not catch on were much less salient. Many more nations had adopted the system since Adams's report, including several in the Western Hemisphere. The UK was also seriously considering metrication at the time. If they had converted, then the ties of trade and of a similar measures tradition might well have influenced the US [1].

The 1870s saw the US participate in the International Commission of the Meter and sign the 1875 Meter Convention. At home pro-metric organizations such as the American Metrological Society engaged in advocacy and education. They realized that Congress was unlikely to pass a law mandating use of the metric system unless the public urged it to do so [8]. Such advocacy was vocal at times, but so was that of anti-metric organizations. America's first anti-metric organization was the International Institute for Preserving and Perfecting Anglo-Saxon Weights and Measures, founded in Boston in 1879. It branded the metric system as the devil's work and claimed that Anglo-Saxon measures derived from the Great Pyramid. This group's wild fantasies did not draw many adherents, but pro-metric sentiment was not very broad-based either [11]. In the absence of widespread or influential advocacy for the metric system, the US government took no measures to promote or adopt it. The next step envisioned

[4] Actually, the resolution to distribute metric standards to the states came a day *before* the vote to legalize the system [9].

and hoped for by the House Committee of Coinage, Weights and Measures in 1866 did not come to pass [8].

In the 1890s, the US once again came close to converting to the metric system, and in 1893 the metric system was put at the foundation of US customary units (Fig. 6.1). The "Mendenhall order" of April 1893, made by Superintendent of Weights and Measures Thomas Mendenhall with the approval of Secretary of the Treasury J. G. Carlisle, was an administrative order, not a law. It formally stated that the office of weights and measures would regard the copies of the new international prototype meter and kilogram recently received by the US as fundamental standards of length and mass. (As a signatory of the Metre Convention, the US received copies of the new standards.) US customary units, the yard and pound, would be derived from these new standards [9].

The Mendenhall order, an effort to promote inter-American trade and the perceived likelihood that the UK was about to convert to the metric system led to US legislative attempts to convert to the metric system in the 1890s and the following years. In April 1896, a bill that mandated metric measures briefly passed the House of Representatives. The bill set dates by which first the federal government and then more general commercial and legal applications would have to be metric. It was adopted by a very narrow margin, but then immediately defeated upon reconsideration and reported back to committee. The House Committee on Coinage, Weights and Measures advanced metric bills each year between 1897 and 1901 without success. After the Great War, advocacy groups on both sides of the metric debate turned directly to the public to attempt to generate political support. Although the issue was discussed in Congressional committees, no bills reached the floor of Congress. The Great Depression sapped the coffers of the groups, and metrication lay mostly dormant until the late 1950s [8].

The launch of Sputnik by the Soviet Union in 1957 prompted much reassessment of science and science education in the US. It is not surprising that weights, measures, and standards received part of that attention in the years immediately following. One action around weights and measures was only indirectly metric, namely an agreement among Australia, Canada, New Zealand, South Africa, the UK and the US to define an international yard and international avoirdupois pound in terms of the meter and the kilogram, respectively. This had the effect of giving the customary units in use in these nations the same value. In late 1958, the British Association for the Advancement of Science began a study of the costs and benefits of metric conversion for the UK, and in early 1959 the American Association for the Advancement of Science started a similar investigation. In that year and most of the next 10 years, resolutions were introduced in Congress to initiate a study of metric conversion and other resolutions to adopt the metric system. None passed until the 1968 Metric Study Act, which required the Department of Commerce to report on the desirability and practicability of increased use of metric weights and measures in the US [8].

The study published 12 volumes on the topic in 1971 [1], including a detailed history of the topic in the US from which much information in this chapter was drawn [8]. The main summary report of the study was titled "A Metric America: A Decision Whose Time Has Come." The study noted that use of the metric system in the US was already increasing, although slowly, and it predicted that US weights and measures would become predominantly metric someday. It considered two main alternative courses of action. One was laissez faire, in which each business or other user of weights and measures decides on its own the timing and extent of metrication without either encouragement or discouragement from the government. The other was a coordinated plan with set timetables within which individual sectors would work out the details and timing of their conversion programs. Notice that compulsory conversion by government fiat was not considered, or at least not presented as a practical alternative. One of the strongest recommendations of the study was that the US increase its participation in international standards-making bodies such as the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC), regardless of any decision on metric conversion [12].

The report found a broad consensus on three questions.

- Is increased metric usage in the best interests of the United States?
- If so, should there be a coordinated national program to change to metric?
- Over how many years should the change be made?

The consensus answers were, yes, increased metric usage would benefit the US, that the nation ought to change to metric in a coordinated way, and that the transition period ought to be about 10 years, at the end of which the nation would be predominantly metric. This set of answers is the bottom-line recommendation of the report. The study presented an interesting set of comparisons that attempted to estimate the costs and benefits of a coordinated metric conversion over 10 years versus an assumed 50-year transition period of drift toward predominant metric use. One of the main benefits of the coordinated approach in this estimate was to reduce the time during which companies and organizations would have to support two measurement systems. Essentially, the coordinated approach would cost more during the transition period than would drift, but the benefits of conversion begin to accrue sooner [12].

From the perspective of 50 years after the issuance of the report, one can see that the assumption of a 50-year period for uncoordinated metric conversion failed to come to pass—although, as will be discussed in Sect. 6.3, the assumption was not unreasonable at the time. Indeed, the subsequent history of the metric system in the US makes clear that the report's title was mistaken: the time for a decision to make the US a predominantly metric nation had clearly not yet come.

Late in 1975 Congress passed the Metric Conversion Act and President Gerald Ford signed it. The Act states [13]:

> It is therefore declared that the policy of the United States shall be to coordinate and plan the increasing use of the metric system in the United States and to establish a United States Metric Board to coordinate the voluntary conversion to the metric system.

In case the word voluntary[5] in the policy statement is not clear enough, the Act later states "Unless otherwise provided by the Congress, the Board shall have no

[5] In the context of this chapter, voluntary refers to the free choice of a business or other user of weights and measures in contrast to legal compulsion imposed by the sovereign government in

compulsory powers." The Board was to be abolished when Congress deemed its mission accomplished.

The Act has been described as a compromise between those who favored compulsory metric conversion and those who wanted no government action on the matter. Subsequent events favored the latter group. The Metric Board did not begin its activities until 1978 after the Senate confirmed President Jimmy Carter's nominees to it; the Senate had not acted on Ford's nominees to the Board before his term expired in 1977. Metric Board publications included a sort of disclaimer: that it had no compulsory power, that there was no target date for conversion, and that conversion was voluntary. The Board was not funded beyond 30 September 1982 [14].

Apparently there was considerable confusion among businesses in the late 1970s about US policy toward metric conversion. So reported a 1978 report by the General Accounting Office (GAO). The report stated that US policy was not to favor one system of measures over another and that the Metric Board's job was to assist entities when and if they decided to convert. One of the GAO report's early headings states "A Decision has not been made" [15]. It seems to me, though, that the plain words of the 1975 Act state that a decision had been made about a policy preference—that the US would benefit from conversion to the metric system—but that no decision had been made to design adequate mechanisms of bringing that preference about. And clearly no decision had been made about when any particular sector ought to convert. The policy preference was reiterated in the Omnibus Trade and Competitiveness Act of 1988, which amended the 1975 Metric Conversion Act by designating "the metric system of measurement as the preferred system of weights and measures for United States trade and commerce." The 1988 Act also required the agencies of the federal government to use the metric system "to the extent economically feasible" by the end of fiscal year 1992 [16]. The 1975 Act remains in effect—albeit ineffective; it has never been repealed but it has been amended as recently as 2021 [17].[6] Conversion to metric units even within the federal government continues slowly. For example, the metric policy page of NIST reports that "the final decision to retire the U.S. survey foot was published in the Federal Register (October 5, 2020) announcing the deprecation date of December 31, 2022." After that time, it is to be superseded by the international foot (defined as 0.3048 m exactly) in all applications. "The preferred measurement unit of length is the meter (m) and surveyors, map makers, and engineers are encouraged to adopt the International System of Units (SI) for their work" [18].

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which the business operates. In Chap. 3, recall, voluntary refers to a free choice of a sovereign government in contrast to a colonial or other occupying force.

[6] The 2021 amendment within the National Defense Authorization Act for Fiscal Year 2022 made no substantial changes, simply updating references to other parts of US law.

6.3 Conclusion: Why is the US Still not Predominantly Metric?

As noted above, the US Metric Study report of 1971 expected that the US would be predominantly metric by now, some 50 years after the report. The report included a map titled "Islands in a Metric World." On that map, nations that had not already become primarily metric or committed to doing so were few and—with the exception of the US—small [12]. Fifty years later, the list of non-metric nations is even shorter, but a world map would look much the same: the US stands out as the visible non-metric exception. Given that the US has held out as an island in a metric world for 50 years, there appears to be no strong sign that it will change.

At the time of the study, though, the situation looked much different—not in the snapshot of the world map, but in the change in that map over the previous decade. The 1960s saw a great expansion of nations converting to the metric system, as can be seen in Vera's compilation of metrication dates [1]. The decade began with newly independent nations, mainly in Africa, adopting the metric system. It ended with a group of English-speaking industrial nations with which the US had strong ties of trade and alliance committing to convert. That group started with the UK (1965), followed shortly by Australia (1969), New Zealand (1969) and Canada (1970). Small wonder that the Metric Study expected that the US would become metric eventually.

Why has it not done so? Vera cites "failure to centralize" and "aversion to compulsion" as the main reasons for the failure of US metrication. No nation adopted the system voluntarily, he points out, so the US efforts to facilitate voluntary conversion were doomed to failure [1]. Steven Treese's analysis is similar. He identifies three aspects of the Metric Conversion Act that made progress toward metrication slow. The costs of conversion (of retooling, for example, and retraining) were to be borne primarily by businesses; conversion was voluntary; and there was no timetable. "The metric system has never been adopted voluntarily in any country, including its native France," he notes. In sum "high cost, no incentives, and voluntary commitment to an open schedule have basically doomed attempts at metrication so far in many sectors of the U.S." [19].

The unwillingness of the federal government to impose a system of measures on its citizens is not limited to recent decades. Recall that Secretary of State Adams questioned the authority of the government to make wholesale changes in the nation's customary measures [7] and that advisors to the Congress that made metric measures legal acknowledged that mandating its use was antithetical to US governmental traditions [8]. Despite a stated preference for adopting the metric system in a coordinated way, the US government has not implemented programs that have moved the nation toward that preference any faster than an expected drift toward it. And having drifted this long as an island in a metric ocean, it appears unlikely that the US will change its course anytime soon.

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