The Foundation of the Metric System in France in the 1790s

THE IMPORTANCE OF ETIENNE LENOIR'S PLATINUM MEASURING INSTRUMENTS

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On 22nd July 1799 the definitive standards of the metric system, the platinum metre and the platinum kilogramme, were ceremonially deposited in the French National Archives (1), and on 10th December 1799 a law was passed confirming their status as the only legal standards for measuring length and mass in France (2). The accurate determination of these standards had occupied a number of outstanding French scientists for ten years, using elaborate equipment partly made from platinum by Étienne Lenoir, a skilled instrument maker. This work had been undertaken after more than a century of discussion. The events surrounding this momentous occasion which now affects all our everyday lives are described here.

Before the Revolution in 1789, France, like most European countries, used weights and measures derived from those of the Romans. The standard weight was the pound of 16 (sometimes 12) ounces which in France was divided further into 8 gros, each of 72 grains. The unit of length was the foot of 12 inches, each divided into 12 lines, though for many purposes a longer unit was preferred – such as the French toise of 6 feet or the British yard of 3 feet. However units with the same name varied in size from country to country: for example, the French pound and foot were each larger than their British equivalents. In Britain most standards had been fixed nationally since the sixteenth century, but in France there were many local variations. This situation caused difficulties for internal and international commerce, made worse by the need to calculate in twelfths, sixteenths or other fractions when converting from one system to another.

When the metric system was first introduced all units were divided decimally, making calculation easier. However, this had become possible only in the late Middle Ages, after 'Arabic' numerals, probably of Indian origin, began to replace Roman numbers. Arabic numerals became common about 1500, but it was not until 1585 that Simon Stevin, a Flemish mathematician showed in his book, "De Thiende", how fractions could be expressed in Arabic numerals using a decimal point. His book was soon translated into French, with an English translation, "Disme: The Art of Tenths", appearing in 1608. As well as explaining decimal arithmetic, Stevin advocated the decimal division of weights, measures and currency (3).

Other mathematicians adopted the decimal fractions. In 1656 in England, Robert Wood, of Oxford, proposed to Oliver Cromwell, the Lord Protector of the Commonwealth after the execution of King Charles I, that the pound sterling should be divided into 'tenths, hunds and thous', but no action was taken and Britain, like other countries, retained a currency with awkward divisions, complicating international trade (4). Wood's interest, however, was solely with currency.

A Decimal System of Measures

The Seconds Pendulum: A Standard Length

An early proposal for a decimal system of measures came in 1670 from a Frenchman, Gabriel Mouton (1618–1694), a parish priest in Lyons with a good knowledge of astronomy and mathematics. He deplored the variety of units of length and proposed a natural unit based on the size of the Earth. This was the length of a minute (a sixtieth of a degree) of longitude, to be called the 'mille' and divided into tenths, hundredths and so on. One thousandth of a mille was called the 'geometric

The trade label used by Étienne Lenoir, dated about 1802. His gold medal (depicted at the top of his label) was awarded by the French government for the encouragement of industry and the useful arts, probably as a prize for work displayed at an exhibition of French industry in 1801 or 1802. He is described here as an 'Engineer for Instruments used in the Sciences' and his business located in the building of the General Depot of the Navy, in the place Vendôme, Paris (28). (Reproduced from A. J. Turner, op. cit., (Ref. 11), by courtesy of the author and the Whipple Museum)

foot' and Mouton suggested that a pendulum of this length set up in Lyon, which would oscillate 3,959.2 times in 30 minutes, would be a convenient and easily verified standard of length.

Mouton's work was known of in Paris, where Jean Picard (1620–1682), an astronomer at the Observatory, proposed that the length of a pendulum beating seconds in Paris should be the standard (the seconds pendulum). One third of this, to be called the 'universal foot', would differ only slightly from the existing Paris foot. However, Picard did not advocate its decimal division. By now it was suspected that the Earth was not a perfect sphere and that the length of both a degree of longitude and the seconds pendulum (which depends on its distance from the centre of the Earth) might vary from place to place (5). This later became an obstacle to international acceptance of the metric units determined in France.

Varying Standards of Mass

During the eighteenth century the lack of an international system of weights and measures affected the development of science as well as commerce. In 1783, for example, James Watt, an amateur chemist as well as an engineer, complained to the chemist Richard Kirwan that he found it difficult to compare some of Kirwan's quantitative results with those of Antoine Laurent Lavoisier (1743–1794), the French chemist, because both had used units with different values. Watt proposed that all chemists should adopt the same pound, preferably that of Paris which was the most widely used in Europe, and that it should be divided decimally (6). In 1789 Lavoisier published his book, "Traité élémentaire de chimie", which marked the origin of modern chemistry. Quantitative data are present in abundance and in its English edition, "Elements of Chemistry" (1790), the translator, Robert Kerr, added an appendix with rules for the conversion of French units to British, see Figure 1. It is noteworthy that Lavoisier expressed some weights as decimal fractions of a pound, as well as the ounces and grains that he had measured in the laboratory.

Commission of Weights and Measures

In France, public discontent with many aspects of life in an absolute monarchy forced King Louis XVI and his government to call elections to the States-General, the only elected parliamentary body, for the first time in 175 years. It met in May 1789 with the new name of National Assembly and assumed the powers of government. Although the Assembly received many complaints about the lack of uniform weights and measures, it was unable to act immediately. In June 1789 the Paris Academy of Sciences independently appointed several members to a Commission of Weights and Measures, with the task of producing a national system. However, as no progress had been made by May 1790, the Assembly formally asked the Academy to act and provided the necessary funds. One member of the Assembly with a special interest in the project was Charles Maurice Talleyrand (1754–1838). He was not a scientist but was almost certainly advised by members of the Academy. He favoured a system based on the length of the seconds pendulum, with the unit of weight defined as the weight of water filling a cube of side equal to a specified fraction of that length. He did not, however, recommend the decimal division of the new units. Talleyrand hoped that the system would be adopted by other countries and proposed that the pendulum should be measured at a place that would be internationally acceptable: sea level half-way between the North Pole and the Equator. This was the 45th parallel, which conveniently crossed the French coast near Bordeaux.

Discussion in Other Countries

The reform of weights and measures was also discussed in the British Parliament, and in July 1789 Sir John Riggs Miller (c.1730–1798) advocated a system based on the length of the seconds pendulum at the latitude of London. When he raised the subject again early in 1790 Talleyrand wrote to him, proposing that Britain and France might collaborate, but Miller's plan was not put to the vote before the dissolution of Parliament on 10 June 1790. Miller lost his seat at the ensuing election and the matter was not raised again in Parliament. At Talleyrand's suggestion the National Assembly made a direct approach to the British government, but on 1 December 1790 the Foreign Secretary informed the French Ambassador in London that the proposed collaboration was not practicable (7).

In 1785 the United States of America, soon after becoming independent from Britain, adopted a decimal currency, and by 1790 Congress was considering a decimal system of measures based on

RULES *for converting French Weights and Meaſures into correſpondent Engliſh Denominations* *.

§ I. *Weights.*

The Paris pound, poids de mark of Charlemagne, contains 9216 Paris grains; it is divided into 16 ounces, each ounce into 8 gros, and each gros into 72 grains. It is equal to 7561 Engliſh Troy grains.

The Engliſh Troy pound of 12 ounces contains 5760 Engliſh Troy grains, and is equal to 7021 Paris grains.

The Engliſh averdupois pound of 16 ounces contains 7000 Engliſh Troy grains, and is equal to 8538 Paris grains.

To reduce Paris *grs.* to Engliſh Troy *grs.* divide by . . .
To reduce Engliſh Troy *grs.* to Paris *grs.* multiply by . . . } 1.2189

To reduce Paris ounces to Engliſh Troy, divide by . . . .
To reduce Engliſh Troy ounces to Paris, multiply by . . } 1.015734

* For the materials of this Article the Tranſlator is indebted to Profeſſor Robertſon.

Fig. 1 The first of Kerr's conversion tables in A. L. Lavoisier's "Elements of Chemistry", translated by Robert Kerr, William Creech, Edinburgh, 1790, p. 485. Professor Robertson has not been identified. English avoirdupois weights were generally used in commerce; troy weights, used for pharmaceuticals and bullion, were preferred by most chemists

the pendulum. This was proposed by the Secretary of State, Thomas Jefferson, who had an interest in science, but after much discussion it was decided to retain the British weights and measures (8). Spain was the only country at this time to show an interest in the French proposals.

The Meridian as a Preferred Standard

Back in France, in September 1790, the Academy of Sciences instructed several members to determine the length of the seconds pendulum and the measures derived from it, but before work was started there was a dramatic volte-face. On 16 February 1791, acting on a proposal by Jean Charles Borda (1733–1799), the Academy

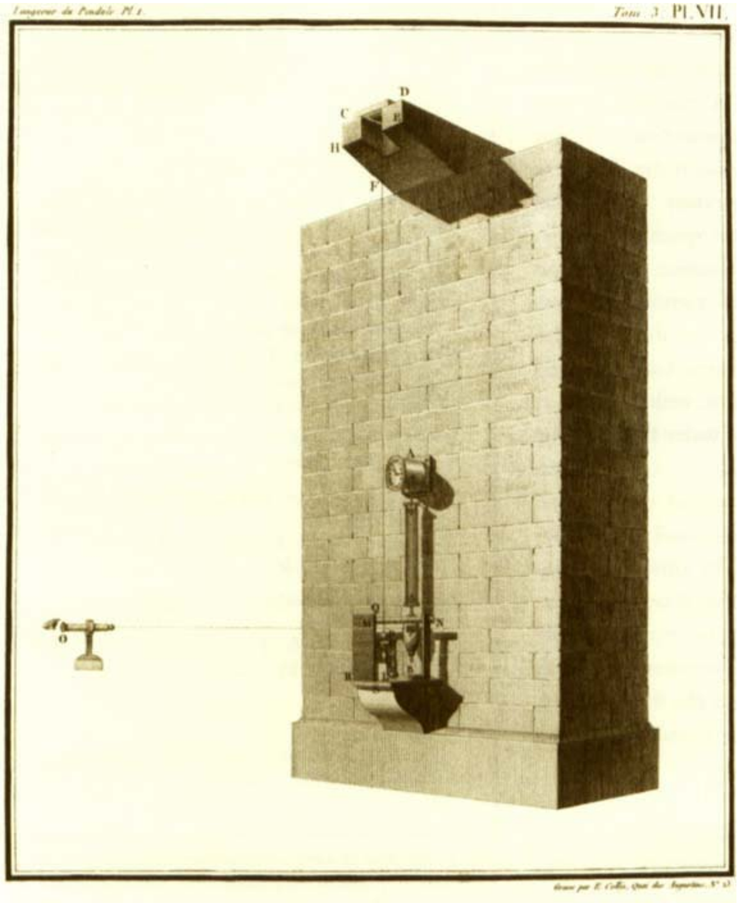


Fig. 2 The pendulum apparatus which Lenoir constructed at the Observatory in Paris. It has a fine iron wire holding a platinum sphere in front of the pendulum of a beating clock. By means of the telescope on the left an observer can follow the movement. The apparatus was enclosed in an airtight case (14)

appointed a new five-member committee to re-examine the proposed fundamental unit of length and on 19 March they reported that they favoured a unit equal to a ten-millionth of the Earth's quadrant, the part of the meridian from the North Pole to the Equator, measured at sea level, and this unit and the units of weight and volume derived from it were to be divided decimally. No explanation was given for the rejection of the pendulum, which had been the preferred unit for more than a century. The academicians pointed out that the Paris meridian passed almost exactly through Dunkirk, on the north coast of France, and only a short distance from the Spanish city of Barcelona, both at sea level, which differed in latitude by 9 degrees and 40 minutes, just over a tenth of the quadrant. The latitudes could be determined by astronomers with the best available instruments and the linear distance by the well established method of triangulation, starting from a carefully measured base line. The total length of the quadrant could then be calculated and the fundamental unit derived from it.

Much of the meridian had been measured in the 1740s, when a large-scale map of France was being prepared, and since then surveying instruments had been improved. Borda, an engineer with a distinguished naval career as a navigator, had recently perfected his repeating circle, which in skilled hands enabled celestial or terrestrial angles to be determined to within a tenth of a second of circular measure. There have been suggestions that the desire of the Academy to demonstrate its effectiveness may have been partly responsible for the abandonment of the pendulum as a standard (9). However, as well as measuring the meridian, the Academy decided to determine very accurately the length of the seconds pendulum at Paris, and the task was undertaken by Borda and Jean Dominique Cassini (1748–1840), director of the Paris Observatory. They completed it at the Observatory in the summer of 1792, before the meridian survey was started. The archives of the Academy are sparse for this period, so nothing is known about any discussions that went on behind the scenes, but it is possible that the measurement of the meridian was intended to draw attention to the importance of the Academy at a time when, like many institutions of the old regime, it was under attack from extreme revolutionaries (10).

Construction of the Apparatus

The apparatus used by Borda and Cassini was constructed by Étienne Lenoir (1744–1825), an instrument maker, born in Mers, a village near Blois in the Loire valley. After being apprenticed to a locksmith he worked in that trade until 1772. He then found employment with a mathematical instrument maker in Paris and studied mathematics by attending one of the free courses available to craftsmen. He set up his own business, supplying specialised astronomical instruments of high quality to leading scientists as well as making mathematical instruments for a larger market, and around 1784 he collaborated with Borda in perfecting the repeating circle (11). His close association with Borda made him an obvious choice to construct the pendulum apparatus at the Observatory, Figure 2. This consisted of a platinum sphere about 1.5 inches in diameter of mass 9911 grains (526.1 g) which was suspended by a fine iron wire about 12 feet long. This oscillated with a half-period of about 2 seconds. As air resistance affected the period, platinum was chosen because it was the metal with the highest specific gravity and thus occupied the smallest volume for a given mass. In order to eliminate errors arising from irregularities in the shape of the sphere, which would alter its centre of gravity, it was, with the aid of a little grease, fitted into an inverted hemispherical copper cup at the end of the wire so that readings could be taken with the sphere in several positions and a mean result calculated.

The wire was suspended in front of the pendulum of a clock beating seconds, and the period of oscillation was determined by an observer who noted the number of seconds between the times when the wire and pendulum coincided, and divided this interval by the number of oscillations. The apparatus was enclosed in an airtight case which had a glass pane through which observations were made with a telescope and, as the aim was to determine the length of the seconds pendulum in a vacuum, allowance was made for variations in air temperature and pressure. There were other minor but significant corrections (12).

The total length of the wire and sphere was measured by means of a platinum scale about 12 feet long constructed by Lenoir. Like the sphere it was made of malleable platinum supplied by Marc Étienne Janety (1739–1820), who had recently perfected his process for its large-scale production (13). The scale, 6 lines wide and 1 line thick, was covered by a slightly shorter copper scale to which it was firmly attached by screws at one end. The metals had different coefficients of thermal expansion, so after calibration the device served as a metallic thermometer as well as a measuring instrument, see Figure 3. The platinum scale was finely ruled by Lenoir. At one end a graduated platinum tongue, sliding in a groove, made it possible to vary the total length, and a vernier scale enabled measurements to be made to within 1/116 line. Corrections were made not only for thermal expansion of the scale but also for its elongation under its own weight. After 20 sets of observations the length and period of oscillation of the wire and sphere were established, and from these figures the length of the seconds pendulum was calculated as 440.5593 lines (99.49 cm) (14). It is interesting to note that at this time the importance of the number of significant figures was not understood.

Borda and Cassini performed these experiments between 15 June and 4 August 1792, but before work could begin on the meridian survey new instruments had to be made, and there was much work for Lenoir and his assistants, who probably numbered fewer than ten. Fifteen months were required for the construction of the

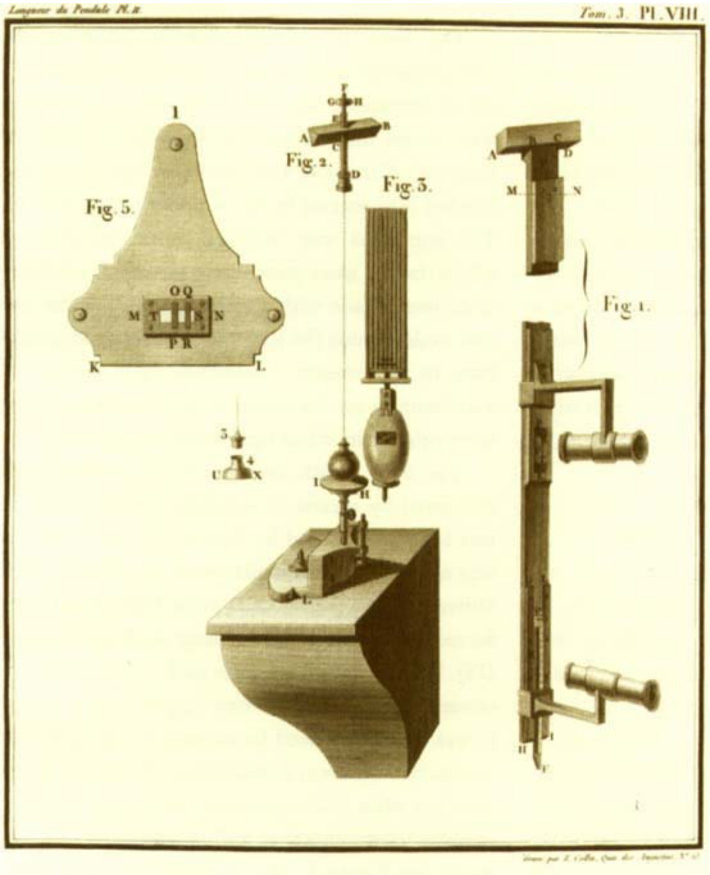


*Fig. 3 Some parts of the pendulum apparatus. The measuring scale is on the right, (*Fig. 1*). The metallic thermometer can be read through the upper microscope, while the vernier on the platinum scale can be read through the lower microscope (14)*

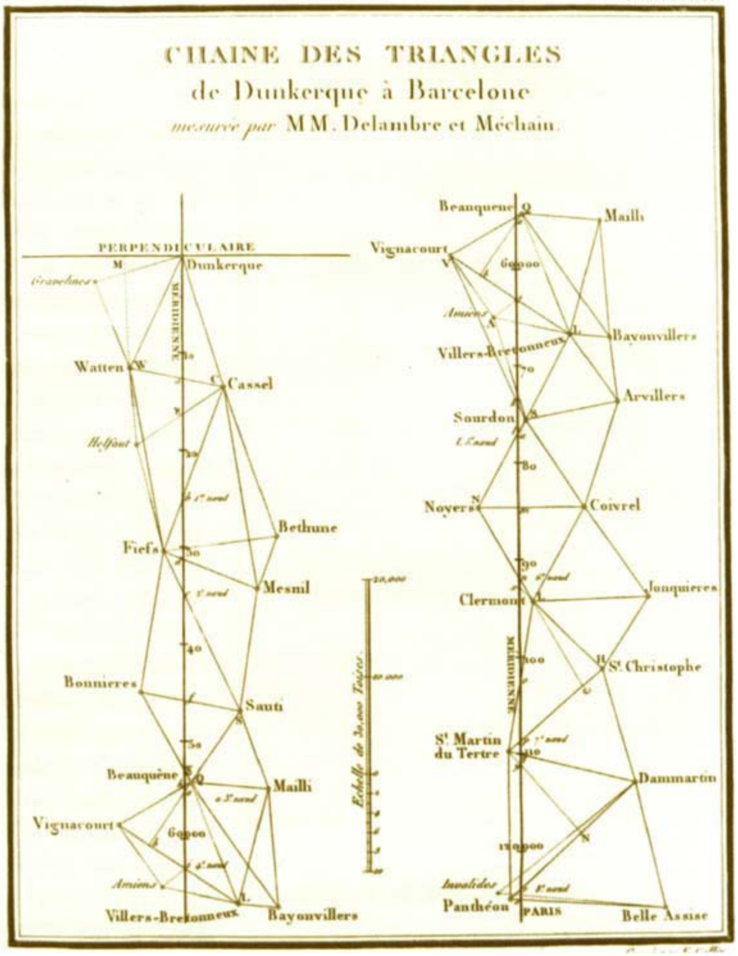
four repeating circles needed by the two teams of surveyors. As Lenoir had experience of making parabolic mirrors for lighthouses he was asked to provide several powerful lamps to enable the surveyors to signal to each other at night or in fog. More importantly, he made four platinum and copper measuring rods similar in size and design to the rule used in the pendulum experiments.

Since the surveyors would have to work in all weathers the thermal expansion of the rods was significant. Borda therefore collaborated with Lavoisier, Treasurer of the Academy and a leading member of the Commission of Weights and Measures, in determining with great accuracy the coefficients of expansion of platinum and copper. At Lavoisier's house they measured very small changes in length by means of an accurate comparator, designed and made by Lenoir, who took part in the work. The work was done between 24 May and 5 June 1793 (15, 16). Being very thin and narrow (see above), the 12-feet long platinum rods had to be handled with great care. Each rested in a shallow groove cut in a wooden plank, and in use was covered by a wooden roof and cloth curtains to protect it from sunlight and minimise expansion and contraction. The planks bearing the rods were each mounted on two tripods, with elaborate precautions to ensure that they remained horizontal.

Dunkirk to Barcelona

The survey from Dunkirk to Barcelona required the accurate measurement of more than a hundred triangles from two base lines, near Melun, south of Paris, for the northern part and Perpignan for the southern, see Figure 4. The teams of surveyors, led by Jean Baptiste Joseph Delambre (1749–1820) in the north and by Pierre François André Méchain (1744–1804) in the south, took seven weeks

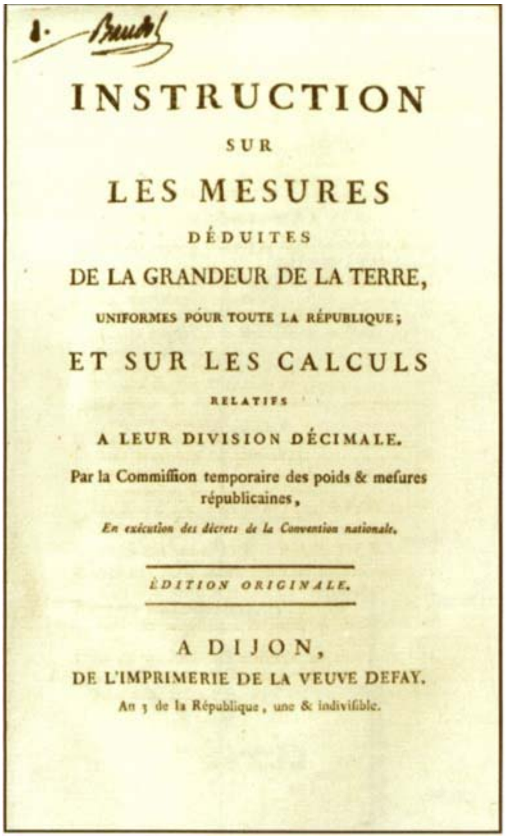
Fig. 4 The northern part of the triangulation, from Dunkirk to Paris. In Paris, the meridian is still marked on the floor and in the grounds of the Observatory. There were over one hundred triangles measured. The base lines for the northern and southern triangles, at Melun (south of Paris) and at Perpignan, respectively, were about 36,000 ft long. The rods had to be moved about 3,000 times for each base line, then accurately aligned and measured (14)



to measure the base lines, each approximately 36,000 feet long and requiring about 3,000 movements of the platinum rods. At each movement two rods had to be precisely aligned, put in exact contact by adjustment of the sliding tongue on one of them, and then measured. Wherever possible the corners of the triangles were high points such as hilltops or church towers, and all the measured distances had to be corrected to allow for variations in height and the curvature of the Earth.

Not surprisingly, the field work and ensuing calculations required far more time than was anticipated, and the surveyors were also handicapped by the fact that after the execution of Louis XVI in January 1793 the French Republic was at war with most of Europe. With their unfamiliar instruments they were sometimes thought to be spies and were harassed by the local population.

In 1794, even though the work was far from complete, the National Convention, the republican successor to the Assembly, wanted to introduce the new weights and measures and the decimal system as soon as possible. Therefore a provisional value for the ten-millionth of the Earth's quadrant was calculated from the results of the survey done in the 1740s and from the best available figures for the latitudes of Dunkirk and Barcelona. This unit, equal to 3 feet 11.44 lines, was named the 'metre', from the Greek 'metron' (measure). After some discussion the Greek prefixes, 'deca', 'kilo' and so on were adopted for multiples of the metre and



INSTRUCTION

SUR

LES MESURES

DÉDUITES

DE LA GRANDEUR DE LA TERRE,

UNIFORMES POUR TOUTE LA RÉPUBLIQUE;

ET SUR LES CALCULS

RELATIFS

A LEUR DIVISION DÉCIMALE.

Par la Commiſſion temporaire des poids & meſures républicaines,

En exécution des décrets de la Convention nationale.

ÉDITION ORIGINALE.

A DIJON,

DE L'IMPRIMERIE DE LA VEUVE DEFAY.

An 3 de la République, une & indivisible.

Fig. 5 The "Instruction sur les Mesures", reprinted in Dijon in Year 3 of the Republic (1794–95) from the original Paris edition of 1793–1794. The first owner, named on the title page, may have been Louis Benigne Baudot (1765–1844), a Dijon lawyer. The book is now in the possession of W. A. Smeaton

Latin prefixes such as 'deci' and 'milli' for sub-multiples. These had been proposed by Claude Antoine Prieur (1763–1832), a former engineering officer who was an early advocate of decimal units and was now a member of the Convention (18). Some time was needed for agreement to be reached about names for the other units, but eventually the cubic decimetre became the 'litre' and the weight of a cubic centimetre of water at its temperature of maximum density was named the 'gramme'.

The New System of Measurements

Lenoir made a provisional standard metre in brass and designed a machine for the manufacture of 660 accurate copies for distribution to all parts of France. In 1794 the government published a book explaining the new system and giving conversion tables for the old and new units (19), see Figure 5. This was reprinted in several provincial towns, in some of which conversion tables for local units were also published. It was decreed that the use of the metric units should be compulsory from August 1794, but this was not in fact achieved until many years later.

Decimal currency, introduced as part of the metric system, was accepted more rapidly, as it was based on the 'franc', a coin containing five grammes of silver which was almost equal in value to the 'livre' of the old regime. Circular measurement was also included in the new system, the right angle being divided into 100 and the circle into 400 'grades', with decimal sub-divisions. Lenoir engraved this scale on three of the surveyors' repeating circles.

The division of the day into 10 hours instead of 24 received hardly any support and was soon abandoned, but the Republican calendar, with a year of 12 months, each month being made up of three 'decades' of 10 days with 5 additional days at the end (6 in leap years), remained in use until 1805.

Preparation of the definitive standards was delayed not only by wartime problems affecting the surveyors but also by political developments in Paris. In July 1793 the Academy of Sciences was suppressed, along with all other organisations that had received funds from the royal government. The eleven scientists working on the new units were allowed to continue, but they suffered a severe blow in November 1793 when Lavoisier, who had been determining the density of water in experiments conducted with the physicist René Just Haüy (1743–1822), was arrested together with all his former colleagues in the Tax Farm, the unpopular private corporation that collected certain taxes under the old regime. By government decree Lavoisier was removed from the Commission of Weights and Measures, as were Borda, Delambre and two other members with links to the old regime (20). On 8 May 1794 Lavoisier and nearly thirty other Tax Farmers were guillotined. He was one of about ten academicians who suffered violent deaths during the Revolution (21).

When the Commission eventually completed its work in 1798 the length of the metre was found to be 3 feet 11.296 lines, slightly shorter than the provisional value of 3 feet 11.44 lines. The observations and calculations of the Commission were checked by a group of foreign scientists who spent several months in Paris at the invitation of the French government, as it was hoped that the new system would be universally adopted. However, Europe was still at war, so only France's allies at the time and neutral countries were represented. These were: Spain, Denmark, the Netherlands, Switzerland and several Italian states. The absentees included Great Britain, Russia, Sweden, all the German states and the United States of America. Even so, the meeting has some claim to be regarded as the first international scientific conference (22). Lenoir made the definitive metre in platinum, and the platinum kilogramme (a more useful standard than the gramme) was made by Nicolas Fortin, another famous instrument maker. It is pleasing to note that they both took part in the ceremony when the standards were deposited in the National Archives – public recognition of the importance of skilled craftsmen in the progress of science.

Slow Adoption of the Metric System

The foreign representatives took accurate iron copies of the standards to their own countries, but there was little enthusiasm for the metric system and its international adoption proceeded very slowly in the nineteenth and twentieth centuries. In 1791 Charles Blagden, the secretary of the Royal Society, had told Sir Joseph Banks, the then president, that in his opinion the French academicians wished 'to divert the attention of the European public from the true amount of their proposal, which in fact is that their measurement of 9 or 10 degrees of a meridian in France shall be adopted as the universal standard' (23). It is possible that Blagden's sentiment was shared by other scientists outside France.

The National Institute, the successor to the Academy of Sciences, decided to permit only metric measurements in its scientific publications, but even in France there was resistance to the metric system in commerce, and the old units were still widely used. In 1812 the Napoleonic government legalised a compromise system with units such as the 'common foot' and the 'common pound', equal to a third of a metre and half a kilogramme, respectively. This gave rise to confusion with the old feet and pounds, and for a time the metric system was almost abandoned. It was not until 1840 that its use became compulsory – fifty years after the reform was initiated (25).

Lenoir's platinum metre, made in 1799, remained in use until replaced in 1878 by an international standard made of iridium-platinum supplied by George Matthey of London (24). The four measuring rods, which had made the accurate determination of the metre possible, were returned from the Observatory to Lenoir's workshop after being inspected by the international commission, but in 1803 they were again taken to the Observatory.

It was decided that the first platinum metre, "No.1", which had been measured by Borda, should remain in the Observatory, but the others were used in 1823 for the triangulation of Switzerland and Alsace, again for a base line near the port of Brest, and finally in 1827 for a base line in south-west France near Dax, Borda's birthplace. In Dax there is now a museum commemorating the life and work of Borda.

The fifth rod, used in the pendulum experiment, was halved in length in 1806 for pendulum measurements by Jean Baptiste Biot and François Arago (26). The 1806 experiments were combined with an extension of the meridian survey from Barcelona to the Balearic Islands, and in 1817, after the end of the Napoleonic wars, Biot carried out similar work in Scotland and extended the meridian to Shetland, publishing the results in 1821 (27). However, he did not use Lenoir's rods for the later surveys.

In 1856, the first rod was compared with one made for the Spanish cartographers, but since then it has been preserved with the others at the Paris Observatory (where they are known as 'les règles de Borda'). They are the largest and most elaborate platinum instruments made in the eighteenth century and excellent examples of the results that can be achieved by the close collaboration of scientists and skilled craftsmen.

The story does not end there, for today the metre and the kilogramme are a well accepted part of the daily life of most people. 'Le Système International d'Unités' is used for measurements by scientists worldwide, with the metre and the kilogram being two of the seven base SI units. From these seven fundamental units, all other units of measurement are derived.

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26 C. Wolf, "Recherches historiques sur les étalons de l'Observatoire", *Ann. Chim. Phys.*, Series 5, 1882, **25**, 5–112 (especially "Les règles de Borda", 54–61)

27 M. P. Crosland, 'Jean Baptiste Biot', in C. C. Gillispie (ed.), "Dictionary of Scientific Biography", Scribner, New York, 1970, Vol. 2, pp. 133–140 (especially pp. 135–136, 140)

28 For the industrial exhibitions, see M. P. Crosland, "The Society of Arcueil. A View of French Science at the Time of Napoleon I", Heinemann, London, 1967, pp. 36–37

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