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Watt's in a name?
Units of power and energy

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Abstract. The origins and adoption of the units of power and energy, watt and joule, are examined, along with their relationships to the achievements of their namesakes, James Watt and James Prescott Joule. The watt and joule came about as part of a group of practical electrical units named and defined in the second half of the nineteenth century. The development of that system and its relationship to the French revolutionary metric system and the current Système International (SI) are outlined. William Thomson (later Lord Kelvin) and the Siemens brothers had important parts in the story; their roles and the units named after them are also described.

Keywords. Nomenclature, units, watt, electricity.

INTRODUCTION

Scientists are accustomed to eponyms, terms derived from the names of people.[1] Often the terms refer to laws, chemical reactions, or other discoveries, named for the putative discoverer of the phenomenon.[2] Fourteen chemical elements have been named directly for scientists, and another two indirectly (named after minerals which had been named after scientists). All 14 of the elements directly named for scientists are synthetic elements, discovered and named only in the years after the Second World War. The scientists so immortalized include some who were themselves important discoverers of elements, such as the Curies, Glenn Seaborg, and most recently Yuri Oganessian; others, such as Copernicus, Einstein, and Mendeleev, discovered no elements, but are honored for other epochal scientific contributions. Constants and units are also often named for scientists. As with elements, so with constants, the connection between the constant and the eponymous scientist is sometimes more direct, sometimes less. The Planck constant, for example, is named for Max Planck, the first scientist to use it in a physical problem.[3] Planck gave the constant the symbol still used for it (h) and a value smaller by just over 1% than the currently fixed value. The Avogadro constant, or its numerical value better known to chemists as Avogadro's number, on the other hand, is a quantity that Amedeo Avogadro never knew, even approximately. Avogadro is best known for proposing that equal volumes of gas contain equal numbers of molecules, but he had no idea of what that number might be. Jean Perrin named the quantity in Avogadro's honor early in the 20th century.[4]

Names of units are the focus of this paper, in particular units of energy and closely related physical quantities such as power and force. The paper was motivated by curiosity over when and under what circumstances the current units of power and energy in the international system of units (Système international, SI) came to be proposed and adopted. As the title suggests, the watt and James Watt are prominently featured. In the course of researching the watt, I learned that the tendency toward eponymy in physical units is more recent than I had expected, dating from the middle to later nineteenth century; that Watt thought more about units than I had realized; that the path from the French revolutionary metric system to the twentieth-century SI was far from straight; and that the watt was first defined as an electrical unit.

The origins of the watt and the joule are so inextricable from the establishment of electrical units and standards in the nineteenth century that the main narrative in the paper (although not its main concern) is how those units and standards came to be. In service of the main focus on eponymy, though, digressions from that narrative include glimpses at aspects of the scientific careers of Watt and Joule and of two other eponyms prominent in the establishment of electrical units, namely William Thomson (later Lord Kelvin) and the Siemens brothers. And in order to round out the main narrative, the relationship of the electrical units to the metric system of units and to the current SI will also be outlined.

ELECTRICAL UNITS CIRCA 1860

Well before 1860, important force laws for electricity and magnetism had been discovered, and the fact that the two apparently different kinds of phenomena were in fact related was also known. The relationship between electricity and magnetism has implications for the units chosen to describe electromagnetic phenomena. For the purpose of understanding the origins of various electrical units, we may take Coulomb's electrostatic force law or Ampère's electromagnetic force law as foundational. Force is a mechanical property with dimensions of $M\ L\ T^{-2}$, where M represents the dimension mass, L the dimension length, and T the dimension time. The choice of one or the other force law as fundamental is arbitrary; however, the choice of either amounts to defining an absolute set of electrical and magnetic units. The set is absolute in the sense that all of the electrical and magnetic units within it would be related to already existing mechanical units.

Choosing Coulomb's law to be fundamental amounts to a choice of electrical units called *absolute* electro*static* units in which electrical charge has dimensions $L^{3/2}\ M^{1/2}\ T^{-1}$; the dimensions of current, then, would be charge per unit time or $L^{3/2}\ M^{1/2}\ T^{-2}$. However, if one takes Ampère's law to be fundamental, different dimensions result. Absolute electromagnetic units have charges of dimension $L^{1/2}\ M^{1/2}$ and currents $L^{1/2}\ M^{1/2}\ T^{-1}$. (For more detail, see the Appendix.)

Within an absolute system of units, further choices are needed before units are defined: one must also select the defining mechanical or dynamical units (that is, of length, mass, 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. (Later scientists would say simply that the centimeter, gram, and second are the *base units* of the cgs system; however, the term base unit was not yet coined.[5] Base unit is a useful term, and I will use it anachronistically in what follows.) The cgs electrostatic unit of charge is therefore $1\ \mathrm{cm}^{3/2}\ \mathrm{g}^{1/2}\ \mathrm{s}^{-1}$. The corresponding unit of current, then, is $1\ \mathrm{cm}^{3/2}\ \mathrm{g}^{1/2}\ \mathrm{s}^{-2}$. In Germany, the preferred set of mechanical base units was the millimeter, milligram, and second;[6] call it mms. Under this system, the electrostatic unit of charge is $1\ \mathrm{mm}^{3/2}\ \mathrm{mg}^{1/2}\ \mathrm{s}^{-1}$ and that of current $1\ \mathrm{mm}^{3/2}\ \mathrm{mg}^{1/2}\ \mathrm{s}^{-2}$. Obviously, electrostatic units have different magnitudes in the cgs and mms systems, even though they are both based on the same fundamental equation. And these units are different than the absolute units based on the electromagnetic force law.

Neither cgs nor mms electrostatic or electromagnetic units were of convenient magnitude for the practical electrical or magnetic applications of the time, such as telegraphy. Submarine telegraph cables were laid in the 1850s, and the first attempt at a transatlantic cable also took place in that decade.[7]

Not surprisingly, a desire for electrical and magnetic units such that a typical laboratory or commercial measurement was comparable in size to the unit (as opposed to many orders of magnitude greater or smaller) emerged around this time. Such units were described as "practical." As we will see below, practical units could be defined in terms of absolute ones (such as the ohm defined as 10^{10} mms units of resistance) or they could be based on arbitrary standards (such as Werner Siemens's mercury standard for resistance). In the later nineteenth century, "practical" and "absolute" were often but not always used as though mutually exclusive, for the term absolute was often applied only to units whose relationship to other units in the system had a numerical factor of 1. Thus, a unit defined as 10^{10} mms units of resistance might be called absolute in the sense that it is defined in terms of specified non-electrical units, although it is not itself "the" absolute unit of resistance in the mms system.

Whether absolute or practical, international units and standards were required for science, industry, and commerce, and they would be much discussed over subsequent decades.

NAMES AND UNITS

Just before the start of the formal and organized efforts to define electrical units and standards outlined below, two engineers on the Atlantic Submarine Telegraph project floated a proposed system of practical electrical units. Latimer Clark and Sir Charles Bright made a presentation at the 1861 British Association for the Advancement of Science (BAAS) meeting and published their paper in *The Electrician* shortly thereafter. "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," they begin. They go on to propose four practical units, not connected to absolute mechanical units. And to illustrate the relationships among these arbitrary units, they suggest "for this temporary purpose let us derive terms from the names of some of our most eminent philosophers, neglecting … all etymological rules".[8]

Quantity	Name	Definition
Tension (i.e., electromotive force)	Ohma	1 Daniell cell
Quantity (i.e., charge)	Farad	Charge induced by 1 Ohma across 1 m^2 plates separated by 1 mm dry air
Current	Galvat	1 Farad per second
Resistance	Volt	Passes 1 Galvat under 1 Ohma tension

The paper by Clark and Bright appears to be the beginning of eponymy in scientific units. Later committees charged with describing electrical units followed their example, sometimes explicitly,[9] although the names on their list were eventually attached to different quantities than they proposed. Clearly, eponymy in other aspects of electrical research was already well established: Clark and Bright refer to Daniell's cells and to a galvanometer without remarking upon those terms.

At the same 1861 conference in Manchester where Clark and Bright made their proposal of electrical units, the BAAS at the behest of William Thomson[10] appointed a committee to report on standards of electrical resistance.[11] The committee initially included several scientists who would become eponyms: Alexander Williamson (whose name is attached to a synthesis of ethers) and Charles Wheatstone (best known for the Wheatstone bridge electrical circuit), as well as Thomson (the Thomson in the Joule-Thomson effect of cooling a gas by letting it expand through a porous plug, later to become Lord Kelvin). The committee rather quickly expanded its purview beyond standards of resistance, noting that such a resistance unit ought to be part of a coherent system of electrical units. The unit of resistance, and indeed, the other units of the system, ought to "bear a definite relation to the unit of work, the great connecting link between all physical measurements".[12]

They advocated basing those electrical units on the "French metrical system" rather than the units in common use in Britain. As might be inferred from their preference for the metric system, the committee was not insular or provincial. Indeed, they solicited opinions from scientists throughout Europe and as far afield as the United States (in the person of Joseph Henry, then Secretary of the Smithsonian Institution and now an eponym for a unit of electrical inductance).[12]

In 1865, the Committee specified a practical standard of electrical resistance. By now the Committee had expanded to 12 members, including such eponymous luminaries as James Clerk Maxwell (equations of electricity and magnetism), James Prescott Joule (unit of energy; see below), and Charles William Siemans (unit of conductivity; see below).[13] The resistance unit was intended to be equal to 10^{10} mm s^{-1}. (An absolute electromagnetic unit of resistance would have dimensions of L T^{-1}, so mm s^{-1} would be the electromagnetic unit of resistance preferred by Germans such as Wilhelm Weber, who had done important work in this area.) The committee wanted their new standard to have "a distinctive name, such as the B. A. unit, or, as Mr. Latimer Clark suggests, the 'Ohmad'".[10] This name was later changed to ohm, which became the first of yet another set of electrical and magnetic units, eventually to be known widely as the practical system. The committee had chosen its unit because it wanted a decimal multiple of a unit already in use (i.e., not something completely arbitrary or unrelated to existing systems) and because a physical standard of approximately this magnitude had already been developed and found convenient.

Members of the Committee threw around ideas for names of units as well as for ways of indicating decimal multiples or submultiples of units, for it was clear that at least some of the units of any coherent system would be of inconvenient size for at least some practical uses. C. F. Varley, one of the committee members, wrote a letter to Thomson in 1865 describing unit names he had discussed with Latimer Clark and Fleeming Jenkin. The letter tells Thomson that Clark had proposed the names Galvad for potential, Ohmad for resistance, Voltad for current, and Farad for quantity (or charge as we would say). The names for one million units would be Galvon, Ohmon, Volton, and Faron respectively. In effect, the multiple 10^6 was proposed to be represented by a suffix, -on. Jenkin objected that denoting magnitude by an ending would lead to confusion, particularly in the case of unclear ("indiscreet") writing, to which Jenkin said he was prone; Varley said that that problem also applied "to me and to you [Thomson]." Varley would like to see a French name on the list, perhaps Ampère for the magnetic pole, but he objected to Galvad "because Galvani discovered next to nothing[14]." We see in Varley's letter the same four scientists that Clark and Bright had in mind four years earlier, now associated with different quantities, but still not with the quantities that would eventually "stick" to their names. We also see an attempt, albeit not adopted, to conveniently refer to multiples of a unit, recognizing that no system would have magnitudes convenient for all applications.

The BAAS Committee on Standards of Electrical Resistance continued to meet and report until 1869, investigating such matters as the relationship between electromagnetic and electrostatic units.[15] In 1872 the BAAS appointed another committee, this one "for reporting on the Nomenclature of Dynamical and Electrical Units." Included on the new committee were four members of the earlier committee: Thomson, Maxwell, Siemens, and Jenkin.[16] The following year, that committee reported a preference for the cgs system for both electrical and dynamical units. It proposed a terminology for expressing decimal multiples by 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 expressing submultiples by 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 suggestion came from committee member G. Johnstone Stoney, who was the lone dissenting voice against selecting the centimeter as a base unit of the recommended system. His argument that the base unit ought not to include a multiplicative prefix was apparently less persuasive than Thomson's favoring a system in which the density of water was unity. This report proposed names for the cgs units of force (dynamy, dynam, or dyne), work (ergon or erg), and power (ergs per second).[17] Looking back from the twenty-first century at the development of eponymy in units, this report appears to be a pause. It mentions the ohm, volt, and farad, practical electrical units previously defined by a BAAS committee that included several of the same members. But for dynamical units, the committee selects names based on Greek roots, a classical language still influential in British higher education.

INTERNATIONAL UNITS

Although the BAAS consulted widely, expressed a preference for the "French metrical system," and proposed an international menu of eponyms, it was a national and not an international body. The 1870s and 1880s would see international bodies and international agreements concerning weights and measures.

Seventeen nations signed the Convention du Mètre in 1875, thereby establishing the Bureau international des poids et mesures (BIPM, International Bureau of Weights and Measures) to be directed by an international committee (CIPM, Comité international des poids et mesures) which itself is under a general conference (CGPM, Conférence générale des poids et mesures) consisting of delegates of the member states. The initial signatories were mainly from countries of Europe or Eurasia (i.e., the Russian and Ottoman Empires), along with a few from the Americas. The principal nation that persists in employing non-metric units in domestic commerce, the United States, was among the original signatories. The United Kingdom, was represented at the 1875 conference that led to the treaty, but it declined to sign until 1884. The BIPM was initially charged with maintaining prototypes of the meter and kilogram, and thermometry and geodesy were also included within its purview. In 1921, coordination of electrical units and standards was added to its range of responsibilities.[18]

The birth of the metric system in revolutionary France during the 1790s is a remarkable story, summarized here in only the briefest outline. The revolution's wholesale overthrow of feudal institutions enabled a widespread centralizing and rationalizing reform of weights and measures to replace a patchwork of regional units. In 1790 Talleyrand, then Bishop of Autun and a member of the National Assembly, brought up reform of weights and measures in that Assembly. After receiving a favorable report, that body decreed in May 1790 that a new set of uniform weights and measures be drawn up. The decree directed the king to "beg His Majesty of Britain to request the English Parliament to concur with the National Assembly in the determination of a natural unit of measures and weights." Louis XVI, still King of France at the time, sanctioned the decree in August.[19] The British declined to participate in the project. The decision to define the meter as the 1/10,000 of a quadrant of the earth's circumference and to determine its value by measuring an arc of a meridian from Dunkirk to Barcelona is described, along with the epic execution of the survey, in *The Measure of All Things* by Ken Alder.[20] Reform of weights and measures continued as the revolutionary government changed (to the Convention), decreed a new calendar, suppressed the Académie des Sciences, and purged the Commission of weights and measures. A law of 18 Germinal, year III, (known elsewhere on the continent as 7 April 1795), defined the new units: the meter, the are (an area of a square with a 10-m edge), the stere (a meter cubed), the liter (the capacity of a cube with side 1/10 m), and the gram (mass of a cube of water with side 1/100 m at the melting point of ice).[21] In 1798, another attempt was made to give the new system international standing by inviting European scientists to participate in the final stages of defining its standards. Invitations were issued by Foreign Minister Talleyrand to nearby countries neutral in the ongoing European hostilities or allied to France (such as the short-lived Batavian, Cisalpine, Helvetian, Ligurian, and Roman Republics).[22] Platinum standards were made for the meter and the kilogram in 1799, and a law of that year defined the units in terms of the standards. The new system was widely used by savants and bureaucrats and taught in the centralized schools, but it did not displace older units in the marketplace for more than a generation afterwards.[21]

At the time of our principal narrative in the 1860s, metric units were widely used in science throughout Europe, but the units considered basic were typically neither the meter (but the centimeter or millimeter) nor the kilogram (but the gram or milligram). In 1869, the French government (Second Empire under Napoleon III) invited representatives from European, Eurasian, and American countries to take part in an International Commission of the meter with an eye toward propagating the use of the metric system in international commerce and constructing new international prototypes of the 1799 standards. This commission, which met in 1870 (just after the start of the Franco-Prussian war) and in 1872, led to the Convention of the Meter in 1875 and the permanent international institutions established therein.[23]

Not long afterward, in 1881, the first International Electrical Congress was held in Paris under the auspices of the French government and in conjunction with an international electrical exposition. It would be the first of many such international electrical meetings in the late nineteenth and early twentieth centuries held at international commercial expositions. Members of this Congress came predominantly from Europe, but Japan was also represented as well as several countries from the Americas.

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 base its units on a cgs foundation; to keep the practical units ohm and volt with their current definitions of 10^9 cgs units of resistance and 10^8 of electromotive force respectively; to define an ampère as the current produced by one volt through one ohm resistance; to define a coulomb as the quantity (charge) such that an ampère is one coulomb per second; and to define a farad as the capacity such that a coulomb in a farad yields a volt.[6]

These extensions to the practical system of electrical units came after some drama inside the conference chamber. They were adopted after the Congress had been adjourned without conducting any business on the previous day, September 20. On that day, the French Minister of Posts and Telegraphs, presiding, opened the meeting and immediately presented his colleague, the Foreign Minister. The latter told the assembly that a telegram had just announced the death of US President Garfield. "He thought that considering the bereavement that fell upon a friendly nation the assembly would wish to show its deep sympathy by immediately adjourning the meeting".[24]

Apparently, some drama regarding the units in question took place behind the scenes at the conference as well. Éleuthère Mascart was secretary of the section of the Congress that dealt with electrical units. He described the delegates enjoying the spectacle of Thomson and Hermann Helmholtz (himself an eponym in thermodynamics) debating heatedly in French, each with his own distinctive pronunciation. The section got bogged down on the standard for the ohm. On the next day, an unofficial group consisting of Mascart, Thomson, William Siemens, Helmholtz, Gustav Kirchhoff (Kirchhoff's laws of circuits), Rudolf Clausius (Clausius-Clapeyron equation), Gustav Wiedemann and Werner Siemens agreed on the definitions of ohm and volt and on appointing an international commission to define the dimensions of the mercury column that was to be the ohm standard. Still later Mascart and Thomson worked out the definitions of ampère, coulomb and farad over a hot chocolate with Lady Thomson (born Frances "Fanny" Blandy). When Mascart read the definitions to the section on September 21, some members were surprised, but after Thomson and Helmholtz spoke in their favor, the group adopted them.[25]

Several more international electrical congresses gathered in various European cities in the 1880s and 1890s, frequently in Paris. At the Paris congress of 1889, practical units of work and of power were adopted. The unit of work was called the joule, defined as 10^7 cgs units of work, the energy dissipated by one ampere through one ohm of resistance. The unit of power was called the watt, defined as 10^7 cgs units, equal to one joule per second. It was also decided that the output of industrial machines would be expressed in kilowatts rather than in horsepower.[26] Here we finally meet our featured units, defined as practical electrical units.

WATT AND JOULE, THE SCIENTISTS AND THE UNITS

James Watt (1736-1819) is well known as an engineer whose improvements to the steam engine powered the industrial revolution in Britain. That aspect of Watt's life and work is well documented elsewhere[27] and will not be discussed here except to note that Watt's name is a particularly appropriate eponym for a unit of power, even though electrical power was outside his expertise. Watt is also known to historians of chemistry for his interest in that discipline, including important work on the composition of water.[28] Watt's interest in units, though, is what will occupy our attention here.

The unit closely associated with Watt during his lifetime, the horsepower, was to be displaced by the kilowatt, at least for electrical generators and other electrical machines if the International Electrical Congress of 1889 was to have its way. The horsepower survives, though, as a unit for rating engines, especially automobile engines. The horsepower was the first important unit of power. Units for power and energy arose before the physical concepts themselves, and they were developed largely in response to industrial and commercial needs. Those who sold energy or heat (in the form of coal, for example) needed a rational basis for pricing their wares. Thomas Savery (1650-1717), who patented a "fire engine" before Watt was born, suggested around 1700 that the rate at which a horse does work would make an appropriate measure of power. Watt made a quantitative estimate of the unit considerably later. Horses were, of course, used as draft animals in agriculture at the time, but they were also used for mechanical power in factories. In that application, they usually walked around a circular track, pulling one end of a lever attached to a shaft, whose gears or other linkage ran a pump or other machine. Watt estimated the average force and speed of a horse pulling a 12-ft capstan lever, and arrived at 33,000 ft lb/min or 550 ft lb/s. This is the definition of the horsepower unit.[29]

Perhaps less well known is Watt's interest in international units and in multiples of 10 to simplify their use. In 1783 Watt wrote to the Irish natural philosopher Richard Kirwan (1733-1812) after experiencing considerable difficulty in converting the weights and measures used by Lavoisier and Laplace to the English weights and measures to which he was accustomed. In the letter, he proposed to define a "philosophical" pound consisting of 10 (philosophical) ounces or 10,000 grains, a philosophical ounce consisting of 10 drachms or 1000 grains and a philosophical drachm consisting of 100 grains. He also advocated "the ounce measure of water" for the measure of elastic fluids, avoiding cubic inches of different sizes. "If all philosophers cannot agree on one pound or one grain, let everyone take his own pound or his own grain," he added, seeing that the simplicity of decimal conversions would at least apply to relative measures, whatever the base unit. But it would be better, he noted, if all agreed on the same pound.[30]

James Prescott Joule (1818-1889) is likewise a celebrated figure. He is best known in the history of physics for quantifying the "mechanical equivalent of heat" and for contributing to the emerging concept of energy as a key physical quantity. Thus, he is a fitting scientist to honor with the name of a unit of energy. Unlike Watt, Joule did important electrical experiments. In the 1840s, he investigated electrical heating and found that electricity gave rise to heat in proportion to the resistance and the square of the current. Indeed, over the course of his career, he explored equivalences among thermal, electrical, chemical, and mechanical effects.[31]

As we have seen, Joule served on the BAAS Committee on Standards of Electrical Resistance. Indeed, he carried out experiments on the resistance of the BAAS unit.[32] Joule also served on the later BAAS Committee for the Selection and Nomenclature of Dynamical and Electrical Units. It is worth noting that Joule was still alive, albeit only for a few more weeks, when the International Congress adopted his name as a unit.[33]

SIEMENS AND THOMSON/KELVIN, THE SCIENTISTS AND THE UNITS

The joule and the watt were adopted internationally in 1889, but they had been proposed earlier in an address by William Siemens, President of the BAAS, at its annual meeting in 1882.[34] The matter of units, both mechanical and electrical, takes up several pages of

Siemens's address. He regrets that the UK "still stands aloof" from the metric system, and he would like the BAAS to ask the government to join the "International Metrical Commission" (BIPM, established by the Meter Convention in 1875). Moving from mechanical to electrical units, he notes with some satisfaction the past work of the BAAS on this matter and acknowledges that their practical system was largely adopted by the previous year's International Electrical Congress. He ventures to suggest two additions to the practical electrical system, one of "magnetic quantity or pole" and one of power. For the former, he suggests the name weber[35] and for the latter he proposes watt. Two further units "may have to be added" before too long, he adds, one for magnetic field and one for "heat in terms of the electro-magnetic system." For the former, he follows Thomson in suggesting the name gauss[36] and for the latter he proposes joule, to be defined as an ampère flowing through an ohm. Both Weber and Joule were still alive at this time when Siemens proposed their names as units.

Siemens's own name is now an electrical unit, although whether the unit is named for him or his older brother Werner is not clear. Werner von Siemens was born Ernst Werner Siemens in Prussia in 1816. In the 1840s, he went into the field of telegraphy. He investigated insulation for laying underground telegraph wires, finding that gutta percha served admirably. He and Johann Georg Halske formed a partnership for manufacturing electrical equipment, including, eventually, electrical generators and motors, electric elevators and railways. A successful inventor and entrepreneur, Siemens maintained a strong interest in basic science. He devised an instrument for measuring alternating current, for example, and helped to fund the German metrology lab, Physikalisch-Technische Reichsanstalt.[37]

William Siemens was born Karl Wilhelm Siemens, also in Prussia, in 1823. Wilhelm went to London in 1843 to try to market an electroplating patent of Werner's. He stayed in England, where he invented a water meter that earned him quite a bit of money. Working with his younger brother August Friedrich (1826-1904), he developed an open hearth method of steel manufacture that used otherwise wasted heat from flue gases to burn off impurities from molten iron and to pre-heat incoming air entering the combustion zone. In 1859, William married Anne Gordon and became a British citizen the same year.[37] Before long, as we have seen, he took an active part in the BAAS, serving on its committees on standards of electrical resistance and on nomenclature of dynamical and electrical units, and eventually serving as President. William became Sir William shortly before his death in 1883, and Werner Siemens became Werner von Siemens in 1888, a few years before his death in 1892.

The Siemenses enter our story of electrical units shortly after the BAAS committee on standards on electrical resistance began its work. In the first report of that committee (1862), we see Werner Siemens among the foreign scientists consulted and we find his letter to the committee included as an appendix.[38] Elsewhere in the proceedings of that year's BAAS conference, we see William ("C. W.") Siemens among the six British scientists added to the committee.[39] Werner's letter calls the committee's attention to a paper he had published in 1860 in Poggendorff's *Annalen* in which he had proposed using a meter-long column of mercury of one square millimeter cross section at 0°C as a unit of resistance, and goes on to describe the advantages of using mercury for such a standard. "Should the adoption of the mercury unit be deemed advisable, I would place at the service of the British Association any further information or assistance in my power".[38] Preliminary measurements relating "Siemens's unit" to other resistance measurements available suggested that the former was very close to 10^{10} times the absolute electromagnetic resistance unit (mms system) defined by Weber. Although the mercury standard was not, in the end, adopted to define the BAAS ohm, the 1881 International Electrical Congress chose a mercury standard (length to be determined) as its standard for the ohm.[40]

When the International Electrotechnical Commission (IEC) acted in 1935 to adopt the MKS (meter, kilogram, second) system of units that later became the SI, the siemens was included as the unit of conductivity, the reciprocal ohm. Which Siemens is the eponymous one (if there is only one), was left unspecified.[41] The name siemens displaced an unofficial name for the reciprocal ohm, namely the mho,[42] which was coined by Sir William Thomson in 1883.[43] Thomson has crossed our path so often that we ought to pause to focus on him and his eponymous unit.

William Thomson (1824-1907) is well known to physicists and chemists, although not necessarily by that name. He is better known as Lord Kelvin, more formally Baron Kelvin of Largs. He was elevated to the peerage in 1892, the first scientist recognized in that way.[44]

Scientists know him for his work on thermodynamics in the 1850s,[45] and if they do not know Kelvin the scientist they know kelvin (K), the unit of thermodynamic temperature. Much of his work in thermodynamics was highly abstract and mathematical; however, he also engaged in practical applications of the science of his day, particularly in electricity and magnetism[46]. "There cannot be a greater mistake, than that of looking superciliously upon practical applications of science," he told an audience at the Institution of Civil Engineers in 1883. Much of the progress he saw in electrical and magnetic measurement over the previous 20 to 30 years, he attributed to the demands of commercial applications such as telegraphy and more recently lighting.[47] During his lifetime, he was celebrated for his role in the transatlantic telegraph cable, and he was knighted soon after its completion in 1866. One later writer even calls Thomson the "ruling spirit behind the work" and deems his work on electrical units and standards "his greatest contribution to science".[48] He invented several instruments for electromagnetic measurements and worked on many committees involving units and electrical standards.[49]

As Thomson's interest in units, standards, and nomenclature suggests, he was a strong advocate for internationally adopted units. During a lecture in the United States in 1884 on the wave theory of light, he made a digression on the virtues of the metric system and the evils of the English system of units. "You, in this country, are subjected to the British insularity in weights and measures," he observed; so he employed feet and inches in the lecture, but he apologized for using such inconvenient measures. He lamented the action of an English government official who had rescinded a recently introduced mandate to teach the metric system in English schools. "I look upon our English system [of weights and measures] as a wickedly brain-destroying piece of bondage under which we suffer," he observed. "The reason why we continue to use it is the imaginary difficulty of making a change and nothing else; but I do not think in America that any such difficulty should stand in the way of adopting so splendidly useful a reform."[50]

As a member of the British House of Lords, Kelvin spoke in favor of a bill on weights and measures in 1904 that would have made metric measures mandatory. After recounting how adoption of metric measures in other countries was achieved without hardship, Kelvin appealed to British self-regard. He said that while the UK might be grateful to France for inventing it and pleased to see how well it has worked in other European countries, it was interesting to note that the idea was born at home: "James Watt laid down a plan which was in all respects the system adopted by the French philosophers seven years later, which the French Government suggested to the King of England as a system that might be adopted by international agreement. James Watt's objects were to secure uniformity and so establish a mode of division which should be convenient as long as decimal arithmetic lasted".[51]

In 1892, the year Thomson was made Baron Kelvin, the British Board of Trade, which had worked with Thomson on practical and legal electrical standards, proposed the name kelvin in place of kilowatt-hour for "the energy contained in a current of 1000 amperes flowing under an electromotive force of one volt during one hour." Kelvin demurred, pointing out that meters manufactured by other instrument makers reading in kelvins would be confusing for users since he had also designed electrical instruments (albeit no supply meters). Kelvin suggested "supply unit" instead. The proposal was revived shortly after Kelvin's death in December 1907. The revived proposal noted that "Board of Trade Unit" could be confusingly abbreviated as BTU, which already stood for British Thermal Unit.[52] As anyone who has seen a household electric bill recently can attest, the kilowatt hour (kWh) is still the standard unit for supply of electrical energy.

Where the kelvin has taken root as a unit name is as the unit of thermodynamic temperature. This is entirely appropriate, for Thomson devised the thermodynamic temperature scale in very nearly its current form in 1848.[53] During his lifetime, it was known as Thomson's absolute scale or Lord Kelvin's absolute scale. In 1948, the ninth CGPM adopted, in principle, the Kelvin scale. It stated that the Kelvin scale "is recognized as the basic thermodynamic scale to which any temperature measurement must eventually be able to relate",[54] an acknowledgment that the scale and its name were well established in practice. Six years later, the tenth CGPM defined the Kelvin scale by fixing the triple point of water at 273.16 degrees Kelvin.[55] And in 1960, the degree Kelvin was listed among the six base units of the newly launched SI.[56] The alert reader may notice the phrase "degree Kelvin," which is not the current name of the unit; the unit and symbol were changed from "degree Kelvin" (°K) to "kelvin" (K) in 1967.[57] The definition of the unit was changed recently; it is now defined in terms of the Boltzmann constant.[58]

FROM INTERNATIONAL ELECTRICAL UNITS TO THE INTERNATIONAL SYSTEM OF UNITS

When we last met the watt and the joule, they had been proposed as units by BAAS President William Siemens and adopted at the International Electrical Congress of 1889. The International Electrical Congress of 1893, held in Chicago, defined a set of "international" units based on cgs electromagnetic unit but defined in terms of practical standards. For example, the international ohm was "based upon the ohm equal to 10^9 units of resistance of the c. g. s. system of electromagnetic units" and "represented by the resistance offered to an unvarying electrical current by a column of mercury at the temperature of melting ice 14.4521 grammes in mass, of a constant cross-sectional area and of the length of 106.3 centimetres." Similarly, the international ampere was described in terms of cgs electromagnetic units (10^{-1} such units of current) and given a realization in terms of a rate of deposition of silver from silver nitrate solution. The joule and the watt were approved essentially as in 1889, but relative to the international ampere and international ohm.[59] The Congress recommended that the nations represented there adopt the international units as legal units, that is, to which regulations would refer. Many nations did so, and that made changing the international electrical units more difficult thereafter, as many legal codes would have to be revised in the aftermath of such change.[60]

At the International Electrical Congress in St. Louis, Missouri, in 1904, no units or standards were defined, but a resolution was adopted to appoint an international commission on standardization and nomenclature for electrical apparatus. That resolution led to the founding, in 1906, of the International Electrotechnical Commission, an organization that continues more than 100 years later. The first president of the IEC was Lord Kelvin.[61] Although no action on units was taken at St. Louis, a proposal that would lead eventually to the SI made its international debut there. Moise Ascoli, head of the Italian delegation at the Congress, read a paper supporting the proposal of his countryman Giovanni Giorgi (1871-1950), and Giorgi's proposal was included in the printed proceedings of the Congress as an appendix to Ascoli's paper.[62]

Giorgi had noticed that the joule, equal to 10^7 cgs units of energy, was also equal to 1 MKS unit of energy, namely to 1 kg m^2 s^{-2}. So it (and the watt) would be natural units in a system whose mechanical foundations were the meter, kilogram, and second. That alone was not enough to bring the other practical electrical units into a coherent system. But if one defined one of the practical electrical units arbitrarily as a fourth base unit, then the other practical electrical units already defined would be part of the new coherent system. The system would be neither electrostatic nor electromagnetic in the sense described earlier in the paper: neither Coulomb's nor Ampère's force law was privileged. In the paper presented at St. Louis, Giorgi selected the ohm as the fourth base unit of the system. As eventually adopted, the ampere was the fourth base unit.[63]

Giorgi had first presented his proposal in Rome in 1901 to the Italian Association of Electrical Engineers, and he also presented it to the Physical Society of London in 1902. His system was little more than an academic exercise for more than 30 years until taken up by the IEC in the 1930s. David Robertson, Professor of Electrical Engineering at the Merchant Venturers' Technical College in Bristol, England, independently devised a similar system, proposing the name newton as the unit of force in the MKS system.[64]

In 1935, the IEC adopted the MKS system, leaving temporarily undecided the choice of the fourth base unit.[63] In the wake of that decision, L. Hartshorn and P. Vigoureux of the British National Physical Laboratory proposed newton as the name of the unit of force in the system: "The name of Newton is universally associated with the idea of impressed force, … and as Newton's name cannot but occur again and again throughout the teaching of even the most elementary mechanics, pronunciation should present no difficulty in other countries".[65] Giorgi was still very much alive at this time. In fact, he was a delegate from Italy in IEC meetings in 1935 and 1938.[66] (Robertson's name and ideas, though, appear to have been forgotten).

In the 1920s and early 1930s, the CGPM seemed to be heading in the opposite direction from the IEC. Having taken electrical matters into its purview in 1921, the CGPM set up a Consultative Committee on Electricity in 1927. (The CIPM operates using consultative committees of various specializations.) In 1933 the CGPM adopted in principle the substitution of absolute electrical units for the so-called international units; in effect, this endorsed cgs units over the practical international units.[67] The CGPM did not meet again until 1948. By that time, it had received requests to adopt a practical international system of units. The International Physical Union recommended development of an MKS system augmented by a practical electrical unit (but did not recommend that physicists drop the cgs system). At this meeting, CGPM instructed CIPM to begin consulting to make recommendations on a single practical system of units.[68] At its next meeting in 1954, the CGPM decided on six base units for its practical system of units, namely the meter, kilogram, second, ampere, degree Kelvin, and candela.[55] And when the CGPM unveiled the SI, newton, joule, and watt were listed among the derived units; they are the SI units of force, energy, and power respectively.[56] As we have already seen, degree Kelvin became kelvin in 1967.[57] The other eponym we have followed in this paper, the siemens, joined the SI as a derived unit in 1971, the same year, incidentally, that saw the mole added as a base unit.[69]

CONCLUSIONS

Although one of the foci of this paper is power (and its units) in the narrow physical sense, the narrative above is full of encounters of science with commercial and political power. We have seen Thomson attribute much of the progress in electrical measurement to demands from commercial applications such as telegraphy and lighting. Indeed, commercial technologies appear to be the driving force for practical electrical units from the telegraphic engineers Clark and Bright to the development of the SI. The international gatherings of electrical scientists and technologists coincided with great commercial expositions, such as the Paris International Exposition of Electricity (1881) and Universal Exposition (1889, which featured the Eiffel Tower), the Columbian Exposition in Chicago (1893), and the Louisiana Purchase Exposition in St. Louis (1904). And even on a side branch of the main narrative above, we have seen that Werner Siemens both practiced science and supported it using the wealth he earned from new electrical technologies.[70]

Over the course of this narrative, we see signs of the much-vaunted international character of science becoming institutionalized, and sometimes being caught up in hostilities that engulfed the wider world. Many international scientific bodies were formed in the early twentieth century, in the aftermath of the First World War. The International Union of Pure and Applied Chemistry (IUPAC) and the International Astronomical Union (IAU) celebrate centennials in 2019.[71] The International Union of Pure and Applied Physics (IUPAP) was founded in 1922.[72] As we have seen, the IEC was formed a few years earlier.

The turmoil of the French Revolution permitted a wholesale change of weights and measures in France. Indeed, that nation saw changes in its calendar, which were rescinded, and a proposed change in time units, which never took hold, as well as the reform of its weights and measures, which endured.[21] International repercussions of the French Revolution limited the active participation of other Europeans in the founding of the metric system mainly to states allied with France or neutral toward them.[19] Given the British reluctance to adopt the metric system even a century later, it seems doubtful that Britain would have accepted the invitation of the King of France to join in devising an international reform of weights and measures even in the absence of international tensions surrounding the French revolution; however, under the circumstances of the revolution, such an invitation was a non-starter.

The failure of the UK in the early twentieth century and the US still to adopt metric units exhibits a reluctance to change from a familiar system. The effort required to change is obvious, perhaps even exaggerated, while the benefits are less evident, particularly since the system already in place appears to work well enough. This sort of inertia is not confined to scientific matters, of course, but scientists are not immune from it. Cgs units were still used in physics courses on electricity and magnetism and in the textbooks used in such courses when I was a student in the 1980s.

Finally, I found it interesting to learn that the attachment of names to formal entities such as units did not arise until the second half of the nineteenth century, although names associated with inventions and apparatus were considerably older. Using Google's Ngram viewer, one can see that eponymous terms like Copernican system, voltaic pile, and Halley's comet were in use in the first half of the nineteenth century. Terms like Boyle's law, Hooke's law, and even Pythagorean theorem, however, only start to appear after 1860 or so.[73]

I have not been able to conclude, even tentatively, what prompted Clark and Bright to use eponyms for unit names in 1860. Their paper (Ref. 8) proposes names based on prominent scientists as if off the cuff, as an expedient for the sake of having names to illustrate relationships. Indeed, the more deliberative discussion of terminology in their paper concerns prefixes to denote multiples of units. I do not know what influenced them to use eponyms for their four proposed units. One of this paper's reviewers wondered whether the sheer quantity of new units that needed names was responsible, and I thank the referee for a plausible suggestion. Tapping a reservoir of names of scientists would have the advantage of furnishing multiple names in a short time—names, moreover, that would have at least some familiarity and association in the minds of the scientists and engineers who would use the names. I found no evidence either in favor or opposed to this plausible hypothesis, other than to note that the BAAS committee on the Nomenclature of Dynamical and Electrical Units opted not to use eponyms for a set of three dynamical cgs units.[17] Still, four names for a pair of authors preparing a conference paper is a large number compared to three names for a committee with time for extensive deliberation. It is clear that Clark and Bright's example of eponymy in units influenced the committees described above. It is not clear, though, that their example had any influence in the appearance of the eponyms Boyle's law, Hooke's law, and Pythagorean theorem that began widespread use in the 1860s.

APPENDIX[74]

Well before 1860, important force laws for electricity and magnetism had been discovered, and the fact that the two apparently different kinds of phenomena were in fact related was also known. The fact that the two phenomena are related has implications for the units chosen to describe electromagnetic phenomena. For the purpose of understanding the origins of various electrical units, we may take Coulomb's or Ampère's force law as foundational. Coulomb's law states that the electrostatic force, F_e, experienced by one point charge, q_1, in the presence of another, q_2, is proportional to the product of the charges and inversely proportional to the square of the distance, r, that separates them.

$$F_e = k_e \frac{q_1 q_2}{r^2} \tag{1}$$

If we take the proportionality constant, k_e, to be 1, a set of so-called *electrostatic* units results, based on the choice of making the fundamental law of electrostatics as simple as possible.

Ampère's force law is a special case of one of the first observed quantitative phenomena that connect electricity and magnetism. It gives the magnetic force, F_m, experienced by two long parallel wires carrying a steady current. In such an arrangement, the force per unit length, L, of wire is directly proportional to the product of the currents, I_1 and I_2, and inversely proportional to the distance, d, between the wires:

$$\frac{F_m}{L} = 2k_m \frac{I_1 I_2}{d} \tag{2}$$

If we take the proportionality constant, k_m, to be 1 (the factor of 2 that appears in the equation comes from this special case of two parallel wires), the result is a set of so-called *electromagnetic* units. The two constants in these laws are not independent: they are related by the relationship

$$\frac{k_e}{k_m} = c^2 \tag{3}$$

where c is the speed of light in a vacuum.[75]

At first blush, there appear to be two choices of units, but in fact, these two choices represent two *families* of electrical units. To specify a set of units requires a choice of a system of mechanical units, that is of units of length, mass, and time. The system favored in Britain for scientific work at this time and eventually adopted more widely was the cgs system. To see how this choice of mechanical units defines electrical units, let us derive some cgs electrostatic units. Coulomb's law, with $k_e = 1$, says that two unit charges separated by unit distance (that is, by 1 cm) experience unit force (1 dyne, or 1 cm g s^{-2}). By rearranging Coulomb's law to solve for two equal charges, one obtains the derived cgs electrostatic unit of charge as 1 cm$^{3/2}$ g$^{1/2}$ s^{-1}. The corresponding unit of current, then, would be one unit of charge per unit of time, or 1 cm$^{3/2}$ g$^{1/2}$ s^{-2}.

To obtain cgs electromagnetic units, rearrange equation 2 to solve for two equal currents with unit values for all other quantities, including the constant k_m. Never mind the numerical value: not even the dimensions are the same for the corresponding quantities in the two systems.

The cgs *electromagnetic* unit of current is cm$^{1/2}$ g$^{1/2}$ s^{-1} (compared to cm$^{3/2}$ g$^{1/2}$ s^{-2} in cgs *electrostatic* units); similarly the cgs *electromagnetic* unit of charge is cm$^{1/2}$ g$^{1/2}$ (compared to cm$^{3/2}$ g$^{1/2}$ s^{-1} in cgs electrostatic units). In the electromagnetic system, $k_m = 1$, so k_e must be equal to c^2.

In the SI, current has a base unit, namely the ampere, A, so the proportionality constant in Ampère's law also has units. Rearranging that law with unit currents, force, and distances shows that k_m has units of kg m s^{-2} A^{-2}. The numerical value of km in these units was taken to be exactly 10^{-7}, just the conversion factor that relates the MKS unit of energy to the cgs unit of energy. The constants k_m and k_e are still related, so

$$k_\mathrm{e} = k_\mathrm{m}c^2 \approx (10^{-7}\ \mathrm{kg\ m\ s^{-2}\ A^{-2}})(3.0\cdot10^{8}\ \mathrm{m\ s^{-1}})^2 = 9.0\cdot10^{9}\ \mathrm{kg\ m^3\ s^{-4}\ A^{-2}}$$

In the SI, the proportionality constants in Coulomb's and Ampère's laws are not expressed in terms of k_e and k_m. Their standard form in SI units are

$$F_e = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2} \quad \text{and} \quad \frac{F_m}{L} = \left(\frac{\mu_0}{4\pi}\right)\frac{2I_1 I_2}{d} \tag{4}$$

Where did the factors of 4π come from? As Edward Purcell explains it in his textbook, "Separating out a factor of 1/4π was an arbitrary move, which will have the effect of removing the 4π that would appear in many of the electrical formulas, at the price of introducing it into some others, as here in Coulomb's law".[76] Equations of electricity and magnetism that use this convention with respect to 4π are said to be rationalized. The constants that appear in these equations are called the electrical permittivity (ε_0) and magnetic permeability (μ_0) of vacuum. Their values are[77]

$$\mu_0 = 4\pi\times10^{-7}\ \mathrm{kg\ m\ s^{-2}\ A^{-2}} \approx 1.257\times10^{-6}\ \mathrm{kg\ m\ s^{-2}\ A^{-2}}$$

$$\text{and } \varepsilon_0 = \frac{1}{\mu_0 c^2} \approx 8.854\times10^{-12}\ \mathrm{kg^{-1}\ m^{-3}\ s^{4}\ A^{2}}$$

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72. IUPAP, About Us.
73. Google Books Ngram Viewer, available online.
74. See, for example, John David Jackson, *Classical Electrodynamics*, 2nd ed., Wiley, New York, 1975, pp 811-821.
75. The value of the ratio was, in fact, a subject of experiments carried out by Thomson and by Maxwell reported by the BAAS Committee on Standards of Electrical Resistance (Ref. 15).
76. Edward M. Purcell, *Electricity and Magnetism*, McGraw-Hill, New York, 1963, pp 449-452.
77. In the redefinition of SI base units that went into effect in 2019, k_m is no longer defined as exactly 10^{-7} but is an experimentally determined number very close to 10^{-7}. See Michael Stock, Richard Davis, Estefanía de Mirandés and Martin J T Milton, "The Revision of the SI—the Result of Three Decades of Progress in Metrology," *Metrologia* **2019**, *56*, available online.