



Introduction to IDTC Special Issue: Joule's Bicentenary History of Science, Foundations and Nature of Science

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Abstract

James Prescott Joule's (1818–1889) bicentenary took place in 2018 and commemorated by the IDTC with a Symposium—‘James Joule's Bicentenary: Scientific and Pedagogical Issues Concerning Energy Conservation’—at the European Society for the History of Science (ESHS & BSHS), 14th–17th September, 2018, in London. This symposium had three main objectives: It aimed specifically to celebrate James Joule's achievements considering the most recent historiographical works with a particular focus on the *principle of conservation of energy*; It served the purpose of discussing the scientific and pedagogical issues related to heat, energy and work and how they are presented in textbooks and worked out in classrooms; It also provided discussions on the present situation of teaching and learning science through the use of History of Science, both in K-12 and college level with an emphasis on energy and related concepts. In the following, the Introduction of this Special Issue on Joule is presented.

Inter-Divisional Teaching Commission is an inter-commission of *Division of Logic, Methodology, and Philosophy of Science and Technology* (DLMPST) and *Division of History of Science and Technology* (DHST) as parts of the *International Union of History and Philosophy of Science and Technology* (IUHPST). The IDTC aims to promote, publish and share world cooperation in the field of the History of sciences, Epistemology and Historical epistemology of sciences, Philosophy of Science/Foundations & Education/Teaching Science, and Nature of Science, understood in the broadest interdisciplinary sense and in agreement with DLMPST and DHST objectives and rules. For further info: <https://www.idtc-iuhps.com> This is the second special issue published under IDTC activities. The first one was guest edited by Pisano Raffaele, President of the IDTC. See the *Introduction* (Pisano and Vincent 2018).

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1 Introduction

Kipnis (2014) could show, after a survey on the extant literature of the time, the extent to which James Joule was influential in his own time (Cfr. Kipnis 2014, p. 2012). Namely, he had found that Joule was the author most cited by his peers working on the mechanical equivalent of heat and the principle of energy conservation between 1845 and 1872 (*Ibidem*, Table 1).

The epistemological works of Hacking (1983) and Baird (2004) took, even though with different approaches, the instruments as agents of the scientific enterprise. Therefore, a new approach emerged with the material turn from the 1990s: the study of the materiality of science acquired its own space in the historiography of science, whether by the study of the practice of its actors or through the instruments that mediated it. Also, research in education has integrated the history of science in the development of a teaching and learning process more relevant, contextualized and with the goal of teaching the *Nature of Science* (NoS; Bächtold and Guedj 2014; Höttecke et al. 2012). Among the strategies developed to infuse the richness of history and philosophy of science in science education is the replication method that is based on the “[...] reconstruction of instruments, materials, and procedures as close to the available sources as possible” (Heering and Hottecke 2014, p. 1484). Almost all textbooks, if not all at some grade, mention James Joule’s paddle wheel experiment. While the schematic of the experiment seems simple and rather straightforward, its usual display comes with several problems: often as presented, the paddle in the can would simply drag the water inside and almost no friction would happen. Of course, this puts problems if students are to interpret what is happening in the can and how could Joule have achieved his conclusion (Cfr. Serway et al. 2008, p. 380).

In line with the material culture of science (Taub 2011), replication method and the use of contemporary materials to construct more or less simplified versions of historical experiments have been developed with James Joule paddle wheel experiment. Sibus (Sibus 1995) has focused on the historical experimental practice through a reenactment of Joule’s experiment. Cibelle Silva and Martin Panuch performed, in the framework of the Oldenburg tradition and HIPST Project (Riess 2000; Höttecke and Riess 2009) another reenactment of the same experiment.¹ In each of these reenactments, the performers, and their reports, brought to light new insights. The brewery culture was highlighted in Sibus experiment while the experiment as was reported originally by James Joule was contrasted with Cibelle’s reenactment. Although this replication method has its difficulties to implement in the teaching and learning of science, more nuanced approaches are suitable to a History and Philosophy of Science approach to teaching and learning. For example, Bächtold and Munier (Bächtold and Munier 2018), proposed an approach based on James Joule’s paddle wheel experiment to grade 11. While James Joule’s experiment is performed and studied, the interpretation that Joule has done of it is not without problems. As Coelho wrote:

Concerning the question of what Joule discovered [...], it could be said that *he found experimental methods for determining the mechanical equivalent of heat*. Joule measured the mechanical power, the heat evolved, established a numerical relation and determined the mechanical equivalent of heat. The justification of this, as conversion from the observable motion of the weights into the unobservable motion of

¹ Via: <https://youtu.be/MBrTDKc9YZ0>.

which heat would consist, is interpretation. This is understandable within the science of that time. (Coelho 2009, p. 972; Author's italic)

Finally, James Joule's contribution to the development of the mechanical theory of heat and, in particular, the experimental finding of the mechanical equivalent of heat and its educational, historical and epistemological relevance to these fields suffice to justify such crucial IDTC symposium.

2 An Historical Context

Lazare Nicolas Margu r te Carnot (1753–1823) stated the chimerical dream of an unlimited production of work by means of a *general working substance* (Carnot 1786, 1778, 1780, §§ 149–160; Gillispie 1971; Gillispie and Pisano 2014; Pisano et al. 2020; Pisano 2017; Carnot 1797, 1803a, b). The source of an unlimited power, evidently correlated with theoretical studies on the conversion of heat-in-work, was analytically formulated by the first law of thermodynamics and its general energy conservation (Joule 1965, pp. 277–281; 1847, pp. 173–176; Clausius 1850, 1865a, b; Thomson 1848, 1851a, b; Pisano et al. 2017, 2018). Finally, Thomson also analytically discussed the second principle of thermodynamics and the necessity of a second thermostat with the aim of executing a passage of heat between a difference of temperature (Thomson 1848–1849, pp. 541–574; 1882–1911, pp. 113–155; 1852, pp. 248–255; Smith and Wise 1989, Chap. 9–11).

In 1789, Antoine–Laurent Lavoisier (1793–1794; *Traite* 1789; 1862–1893) as well as other chemists of his time, searched for the basic principles of this new theory in a revolutionary fashion. Nevertheless, these new principles were different from those of Newtonian Mechanics (Bussotti and Pisano 2014; Pisano and Bussotti 2016; see also Pisano 2019; Bussotti and Pisano 2019). Lavoisier's conceptualization rejected the traditional system of the principles of the four elements directing his attention to new ones such as *chaleur*, *calorique* and *lumiere* (Lavoisier 1789, I, pp. 12–17); with respect to the Newtonian paradigm, it could be considered—*à la* Kuhn—such as revolutionary new coming theory out of mechanical *normal science* in the period of time. Lavoisier and Pierre Simon de Laplace (1749–1827) carried out remarkable research on this (Lavoisier and Laplace 1784). Generally speaking, scientific knowledge on the matter took two main paths, one based on the properties of gases (Newtonian kinetic model of gases) and another one based on the efficiency of heat machines, which naturally included the gas theory. The heat machines would (later) developed into thermodynamics.

In 1824, Nicolas L onard Sadi Carnot (1796–1832) presented the basics of the thermodynamics (2nd principle only) in his only published book—*R flexions sur la puissance motrice du feu* (Carnot 1824; hereafter *R flexions*). He dealt with heat machines and gas theory by: a) *the caloric hypothesis mixed with a weak heat concept*, b) *the cycle* and c) *ad absurdum proof theorem* (atypical for a physical science at that time). The *impossibility of a perpetual motion* was linked to the *state of a system*, *reversible processes* and *cycle* (four phases). In his unpublished *Notes sur les math matiques, la physique et autres sujets* (Carnot S.d.) slightly made indirect use of the hypothesis on *puissance motrice* conservation/heat-work (Carnot 1878a, pp. 134–135). He provided a cycle (three phases) in his unpublished *Recherche d'une formule propre   repr senter la puissance motrice de la vapeur d'eau* (between November 1819 and March 1827; *Ivi*). At the beginning of the discursive part of *R flexions*—and at the end of his celebrated theorem—he claimed that *work can be obtained every time there is a difference in temperature between which heat flows*.

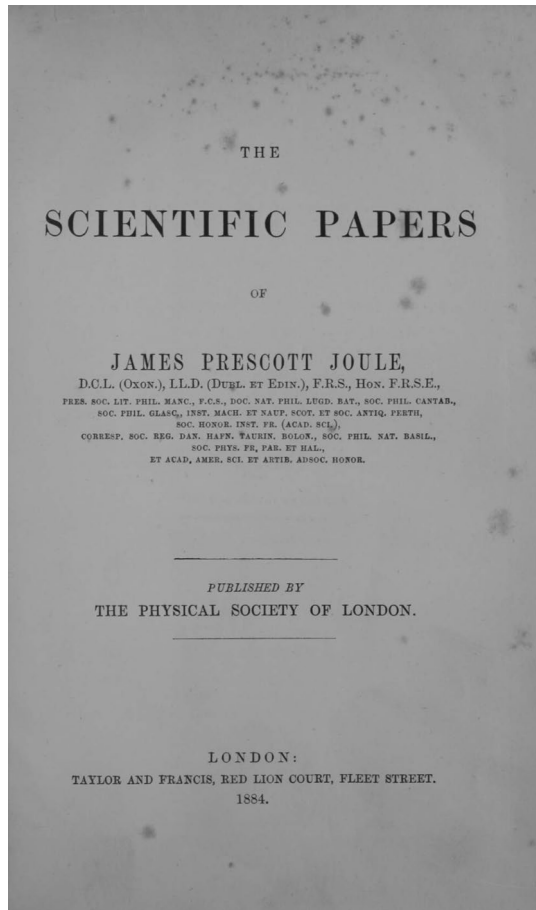
He proposed a different manner to close his own cycle (displayed by cylinders only) and determined (erroneously) the mathematical function of the efficiency for an heat machine (Reuleaux 1876). In French society, (at the Polytechnic school) Clapeyron, a friend of Sadi's, mathematically exposed the *Réflexions in Mémoire sur la puissance motrice de la chaleur*, adding (Clapeyron 1834, pp. 153–190) what nowadays we wrongly read as “Carnot's cycle” (Cfr. Clausius 1850, pp. 368–397; pp. 500–524; p. 379; Volta 1799, 1800a, b, 1918–1929; Poisson 1823; Reech 1853; see also Cardwell 1989a, b). This analytical reinterpretation of the so-called *PV diagram (loop, or Clapeyron diagram)* of the cycle did not have a metric (i.e., with respect to *Descartes' diagram*; Schuster 2013).

3 James Prescott Joule

English (Salford, Lancashire) physicist—and—mathematician, James Joule is one of the most important scientific figures of all time. Son of a brewer, he built his own laboratory in the family's brewery in order to pursue his scientific vocation at his leisure. His many experiments and findings led him to establish relationships between electricity, chemistry (Scerri 2013) heat—and—mechanical work. One of his major accomplishments was the *Mechanical Equivalent of Heat*, which ultimately led to a contribution for the modern principle of conservation of energy as extension of the mechanical conservation of energy when including heat and temperature in the phenomena (Pisano's works; Gillispie and Pisano). His achievements prompted the scientific community to honour him by giving his name to the unit of energy, the joule (J). His works have been mainly collected between 1884 and 1887 (Figs. 1, 2).

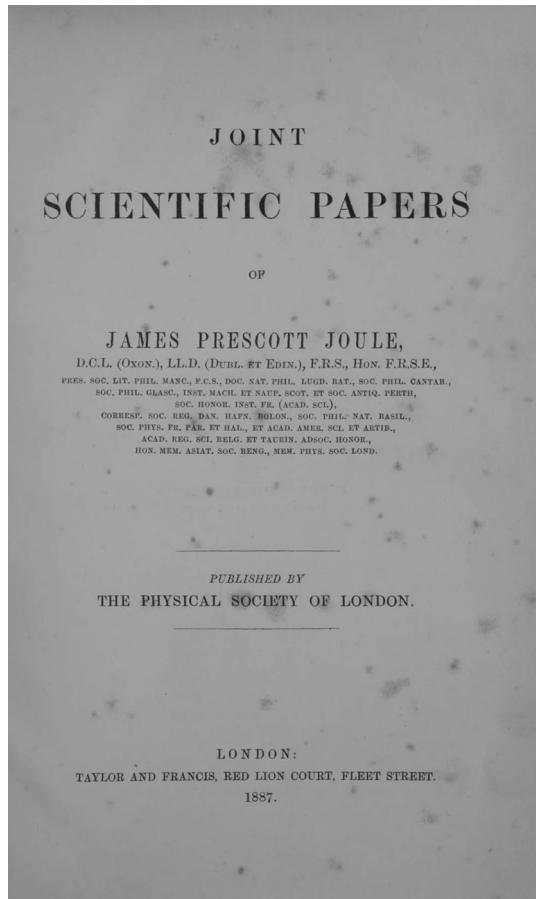
His parents were Benjamin Joule (1784–1858), a rich brewer, and his mother was Alice Prescott (1788–1834). James Joule was born on the 24th of December, 1818, on Christmas Eve, in Salford and was the second son of the couple who had five children: Benjamin, James, John, Mary and Alice (Fig. 3). He was mostly home-schooled with his elder brother Benjamin, due to his “delicate and under treatment for the spine” (Reynolds 2011, p. 26); until 1842 he was at their father's house after which he got sent to the Manchester *Literary and Philosophical Society*, where he studied geometry and arithmetic and became John Dalton's (1766–1844) pupil for two years (Reynolds 2011)—who became notably famous for his atomic theory and work on colour blindness—. After Dalton suffered from health problems due to the consequences of a stroke, Joule was greatly influenced by chemist William Henry (1774–1836), who gave his name to the law of gas dissolution in liquids, engineer Peter Ewart (1767–1842), who had a notably role in the development of calorimetry/thermodynamics. When his father became ill, James and his brother took the direction of the family's brewery; however as his interest in science had not faded, he did not take an active role in the direction of the brewery and instead installed his laboratory inside the brewery and dedicated a lot of his time experimenting and researching as he was very fascinated with electricity and electromagnetism in general. It is through his interest in electrical phenomena that Joule then began to get interested in heat. He studied the electrolysis of water and was very interested by—nowadays known such as—the Peltier Effect (Joule 1884). He also collaborated with William Thomson, Lord Kelvin (1890–1895) whom he met at the Oxford Meeting of the British Association for the Advancement of Science and with whom he became friend (Fox 1969). Although Joule—like other bordering scientists at that time—did not play any academic role—teaching—, he was named F.R.S, Fellow of the Royal Society of London in 1850.

Fig. 1 Joule's Scientific Papers, Frontispiece. 1884.
Source Joule's Scientific Papers|Attribution-ShareAlike 4.0 International (CC BY-SA 4.0)|Fondazione Biblioteca Europea di Informazione e Cultura (BEIC). <https://www.beic.it>



Joule dealt with calorimetry and became one of the most important contributors to the forthcoming, at that time, thermodynamics. He embarked on a journey to quantify the relationships between heat and work by means of very diverse experiments of extraordinary precision for the time. Even if he might have seemed to have progressed by slow but steady increments and improvements, this provided researchers with the very solid experimental foundations they needed in the 1840s (Joule 1840, 1841a, b)—which in comparison to other pioneers in the field of energy conservation—is a quality which many other brilliant minds lacked, such as Julius Robert von Mayer (1814–1878). Particularly, we remind that Sadi Carnot obtained (*Notes sur les mathématiques, la physique et autres sujets*, III, 7v; see also Carnot 1878b, p. 95, 1986, p. 191; Gillispie and Pisano 2014) the value of the heat equivalent—20 years before Mayer (Mayer 1842a; see also 1840, 1842b). In this sense, he discarded the theory of conservation of caloric and presented the conservation of “puissance mécanique” (Carnot [1824]1978, p. 248). The estimate value proposed by Sadi Carnot (Cfr. Carnot 1878b, pp. 94–95; see also 1878a; Cfr. Carnot 1986, pp. 191–192) for the mechanical equivalent of heat of 370 kg/cal is not so much farther from the correct accepted value (427) than Mayer’s later determination (365 kg/cal). The difference is only 11% (Gillispie and Pisano 2014, Chap. 9–10; Hoyer 1975; Edmunds 1902, p 127).

Fig. 2 Joule's Scientific Papers, Frontispiece. 1887. Source Joule's Scientific Papers|Attribution-ShareAlike 4.0 International (CC BY-SA 4.0)|Fondazione Biblioteca Europea di Informazione e Cultura (BEIC). <https://www.beic.it>



His first paper (1838)—as collected paper by Physical Society of London—was *Description of an Electro-Magnetic Engine* for William Sturgeon's (1783–1850) *Annals of Electricity* (Joule 1838, 1884, pp. 1–3). The publication was accompanied by an explicative letter addressed to the editor (Fig. 4), as well.

At the age of only twenty, he began a series of personal experiments on the subject. One of his objectives was to design an electric motor to replace steam-engines (Cfr. Ostwald 1912). On May 28, 1839, he wrote a letter in which he shared his thoughts on the future replacement of steam engines by electro-magnetic engines and also described how he thought that there might exist a possibility to use the latter in such a way that the costs of running them might ultimately be reduced to zero:

I can scarcely doubt that electro-magnetism will eventually be substituted for steam in propelling machinery. If the power of the engine is in proportion to the attractive force of its magnets, and if the attractive force is as the squares of the electric force, the economic effect will be in the direct ratio of the quantity of electricity, and the cost of working the engine may be reduced ad infinitum. It is, however, to be deter-

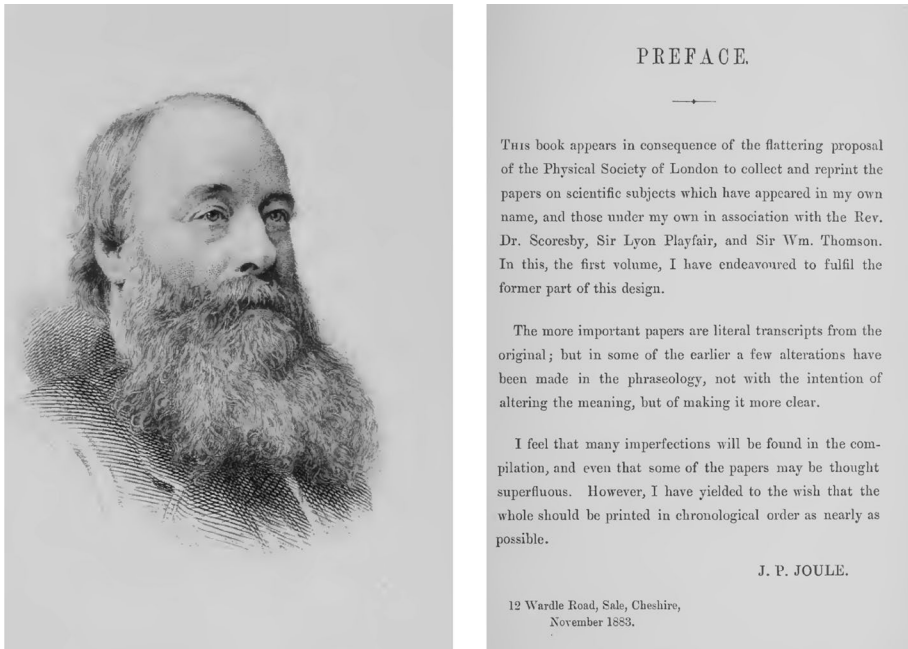


Fig. 3 Joule's Image and Preface, preliminaries pages (Joule 1884). *Source* Joule's Scientific Papers/Attribution-ShareAlike 4.0 International (CC BY-SA 4.0)/Fondazione Biblioteca Europea di Informazione e Cultura (BEIC) <https://www.beic.it>

mined how far the effects of magnetic electricity may disappoint these expectations.² (Joule 1839, p. 135; 1884, p. 14).

However, he soon realized that the work done by the engine had to come from the zinc in the cell batteries and thus employed himself to measure the yield rate involved. Indeed as a businessperson, he felt that this might be profitable, but found out that burning coal was much more economical than using zinc:

Now the duty of the best Cornish steam-engine is about 1,500,000 lb. raised to the height of 1 foot by the combustion of a lb. of coal, which is nearly five times the extreme duty that I was able to obtain from my electro-magnetic engine by the consumption of a lb. of zinc. This comparison is so very unfavourable that I confess I almost despair of the success of electro-magnetic attractions as an economical source of power; for although my machine is by no means perfect, I do not see how the arrangement of its parts could be improved so far as to make the duty per lb. of zinc superior to the duty of the best steam-engines per lb. of coal. And even if this were attained, the expense of the zinc and exciting fluids of the battery is so great, when compared with the price of coal, as to prevent the ordinary electro-magnetic engine from being useful for any but very peculiar purposes. (Joule 1841a, p. 220, 1884, p. 48).

² We note that the wording of this paper, included this quotation is quite different in the Scientific papers: "I can hardly doubt [...] economy [...] ad infinitum." (Joule 1884, p. 14 [pp. 10–14] see also pp. 15–18).

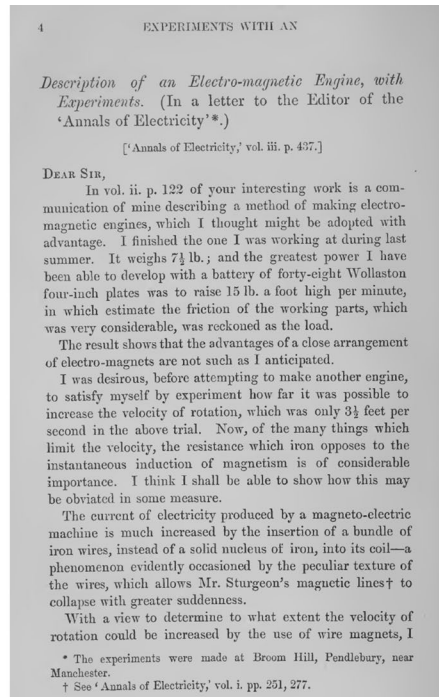
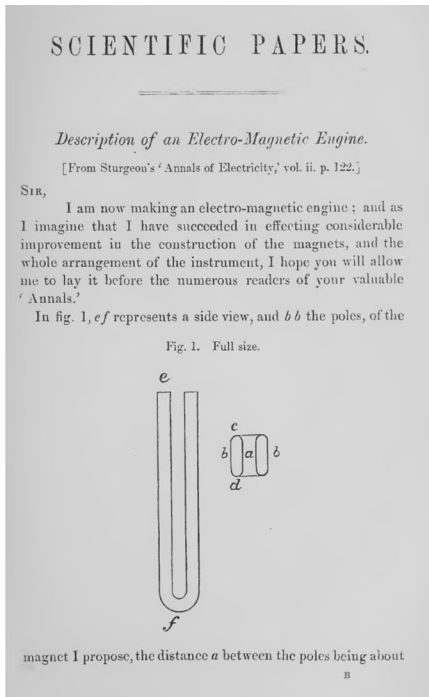


Fig. 4 Joule's first paper on Electro-Magnetic Engine and related letter to the Editor, (Joule 1884, p. 1, p. 4). *Source* Joule's Scientific Papers/Attribution-ShareAlike 4.0 International (CC BY-SA 4.0)/Fondazione Biblioteca Europea di Informazione e Cultura (BEIC) <https://www.beic.it>

During his experimentations he noted that with the electric currents he used, his wires were heating, thus implying that some kind of loss occurred. At the time, this was a known fact, however, Joule decided to study this phenomenon (Cfr. Fox 1969) and investigated the generation of heat in chemical, electrical and mechanical experiments. This finally led him to a number of findings, and in particular to find the relationship between the heat generated in a conductor, the resistance and the current flow, what is now usually referred to as the Joule Effect:

17. We see, therefore, that *when a current of voltaic electricity is propagated along a metallic conductor, the heat evolved in a given time is proportional to the resistance of the conductor multiplied by the square of the electric intensity.* (1884, p. 65, author's italic; 1841, p. 260).

On February 16th, 1841 (Joule 1841a, pp. 219–224), Joule reported that, a certain Mr. F. D. Arstall (Joule 1842, p. 76), suggested to him a “new form of electro-magnetic engine”. It seems, following this suggestion, that Joule described how he underwent an inquiry of the phenomenon with a series of experiments in order to verify if “the effects of magnetism upon the dimensions of iron and steel bars” (Ivi, pp. 76–87), which is better known nowadays as magneto-constriction, could be used in a useful way to generate “motive power” (Ibidem). On that, he wrote:

A few weeks ago an ingenious gentleman, of this town, suggested to me a novel form of electro-magnetic engine. He was of opinion that a bar was increased in length by receiving the magnetic influence; and that, although the increment was perhaps very small, it still might be found valuable as a source of power on account of the great force with which it would operate. At that gentleman's request, I have entered into experiments to ascertain whether his opinion was correct, and if so, into a calculation whether the new source of power might be advantageously adopted for the movement of machinery. (Joule 1841a, p. 221, 1884, p. 48). [...] Their results [of some experiments] proved *it to be very nearly proportional to the intensity of the magnetism and the length of the bar.* (Ivi, p. 222, Ivi, p. 49)

It also should be noted that in the same production, Joule argued that the phenomenon of magnetic saturation, which happens when the magnetization of a ferromagnetic material under the effects of an external magnetic field increases with the external magnetic field up to a certain point. However, as he proposed a first possible explanation for the phenomena he observed, he felt that it was erroneous and thus did not manage to provide a satisfying conclusion:

The only way in which it can account for the fact that iron, after receiving a certain quantity of magnetism, is incapacitated from receiving a further supply, or becomes saturated, is by supposing that the electricity which revolves around each atom of iron has a centrifugal tendency. The velocity of the electric currents around the atoms of iron will tend to be proportional to the inductive influence which urges them, and if the electricity be not endowed with centrifugal force, it is difficult to say why it should refuse to travel beyond a certain velocity; and in that case the phenomenon of saturation is left unexplained. If, however, the momentum of electricity, and its consequent centrifugal tendency when rotated, be supposed to exist, the currents will be prevented from going beyond a certain velocity by their interference with one another.³ (Joule 1841a, p. 223; 1884, p. 51)

Indeed, heat and other thermal effects were thought to be involving an ambiguous substance called the *caloric* (Pisano 2003, 2010; Gillispie and Pisano 2014, Chap. 8–9) which was present everywhere in the universe and that bodies could possess in different quantities and exchange in various ways; either by contact, conduction, convection or at a distance. During the 1840s, with his investigations and analysing his experimental results he came to the understanding that heat was related to electricity, chemical reactions and mechanical effects such as friction. For instance, in his work “On the Calorific Effects of Magneto-Electricity, and on the Mechanical Value of Heat” read before the Section of Mathematical and Physical Science of the British Association, meeting at Cork on the 21st of August 1843, he wrote:

The quantity of heat capable of increasing the temperature of a pound of water by one degree of Fahrenheit's scale is equal to, and may be converted into, a mechanical force capable of raising 838 lbs. to the perpendicular height of one foot. Among the practical conclusions which may be drawn from the convertibility of heat and mechanical power into one another, according to the above absolute numerical relations, I will content myself with selecting two of the more important. The former of

³ We again note that that the wording of this paper, included this quotation is quite different in the Scientific papers (Joule 1884, p. 51).

these is in reference to the duty of steam-engines; the latter, to the practicability of employing electro-magnetism as an economical motive force. (Joule 1843, p. 441; 1884, p. 156).

Joule was trying to establish a definite relation between heat and mechanical power. In this same paper, he then commented on Count Rumford's, also known as Benjamin Thompson (1753–1814), experience and described how his own investigation led to the same conclusions:

We shall be obliged, after all, to admit that Count Rumford was right in attributing the heat evolved by boring cannon to friction, and not (in any considerable degree) to any change in the capacity of the metal. I have myself proved experimentally that *heat is evolved by the passage of water through narrow tubes*. (Joule 1843, p. 442; 1884, p. 157)

A result that he confirmed several years later in his *On the Mechanical Equivalent of Heat*⁴ (read 1849, 21 June and published on 1850):

Heat is a very brisk agitation of the insensible parts of the object, which produces in us that sensation from whence we denominate the object hot; so what in our sensation is heat, in the object is nothing but motion—Locke. “The force of a moving body is proportional to the square of its velocity, or to the height to which it would rise against gravity.”—Leibnitz. [...]. The first mention, so far as I am aware, of experiments in which the evolution of heat from fluid friction is asserted, was in 1842 by M. Mayer⁵ who states that he has raised the temperature of water from 12 °C to 13 °C, by agitating it, without however indicating the quantity of force employed, or the precautions taken to secure a correct result. (Joule [1849] 1850, p. 61, p. 63; 1884, p. 298, p. 302; Figs. 5, 6)

As above cited, however, even if Mayer (and before him, Sadi Carnot) obtained his results in a completely independent way, Joule was using a much more thorough method of investigation. Joule concluded with what might—or might not, because of the hereby religious standpoint casting a shadow on an unbiased objectivity—be considered a first intuition regarding a subtle underlying principle which would become what we now understand as the conservation of energy:

I shall lose no time in repeating and extending these experiments, being satisfied that the grand agents of nature are, by the Creator's fiat, *indestructible*; and that wherever mechanical force is expended, an exact equivalent of heat is *always* obtained. (Joule 1843, p. 442; 1884, pp. 157–158)

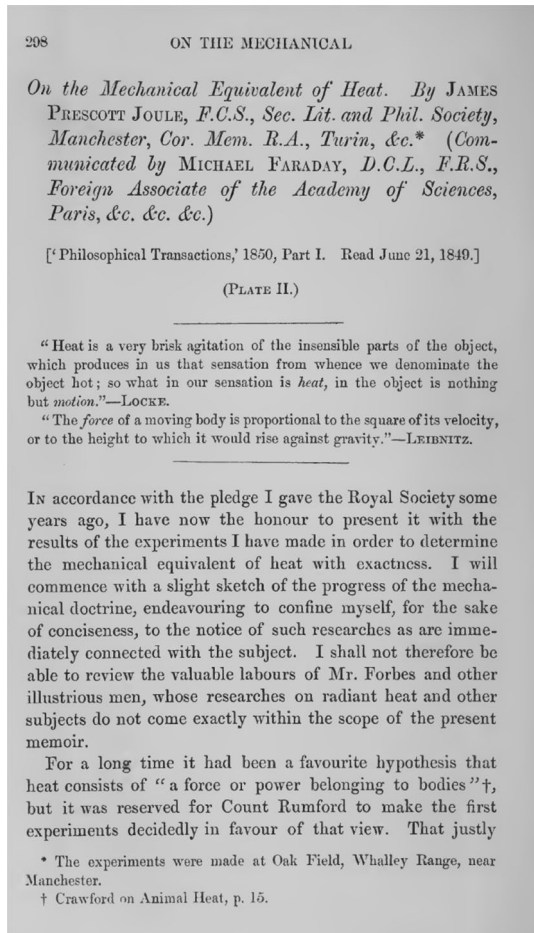
As he linked heat with electricity, chemical action—and “mechanical force”—the latter being what would be called work nowadays:

[...] I had before endeavoured to prove that when two atoms combine together, the heat evolved is exactly that which would have been evolved by the electrical current due to the chemical action taking place, and is therefore proportional to the intensity

⁴ "Brit. Assoc. Rep. 1845, Trans. Chemical Sect. p. 31. Read before the British Association at Cambridge, June 1845.]" (Joule 1884, p. 202). Joule wrote several issues on the subject before completing its final account on the subject in 1850 (Joule 1884).

⁵ Annalen of Wöhler and Liebig, May 1842.

Fig. 5 *On Mechanical Equivalent of Heat*. Joule 1884, p. 298 [pp. 298–328]. Source Joule's Scientific Papers/Attribution-ShareAlike 4.0 International (CC BY-SA 4.0)/Fondazione Biblioteca Europea di Informazione e Cultura (BEIC) <https://www.beic.it>



of the chemical force causing the atoms to combine. I now venture to state more explicitly, that it is not precisely the attraction of affinity, but rather the mechanical force expended by the atoms in falling towards one another, which determines the intensity of the current, and consequently the quantity of heat evolved; [...] (*Ivi* p. 443; 1884, p. 158).

In his *On the Changes of Temperature produced by the Rarefaction and Condensation of Air* published in the *Philosophical Magazine*, vol. XXVI series 3 in May 1845, Joule was investigating the relation between changes of temperature, and thus heat, in regards to changes in the density “of gaseous bodies”. Although they studied the phenomenon in which “the temperature of air is decreased by rarefaction and increased by condensation” (Joule 1884, p. 173), it was Dalton who was “the first who succeeded in measuring the change of temperature with some degree of accuracy” (*Ibidem*). The data he gathered then led him to write:

The results are, however, such as might have been deduced *à priori* from any theory in which heat is regarded as a state of motion among the constituent parti-

Fig. 6 The first Table of “1st Series of Experiments” on mechanical equivalent of heat (Joule 1884, p. 307).

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EQUIVALENT OF HEAT. 307						
TABLE I. (continued).						
No. of experiment and cause of change of temperature.	Total fall of weights in inches.	Mean temperature of air.	Difference between mean of columns 5 and 6 and of column 3.	Temperature of apparatus.		Gain or loss of heat during experiment.
				Commencement of experiment.	Termination of experiment.	
7 Radiation ...	0	59.888	0.209-	59.677	59.681	0.004 gain
7 Friction ...	1254.02	60.076	0.111-	59.681	60.249	0.568 gain
8 Radiation ...	0	58.240	0.069+	58.871	58.828	0.043 loss
8 Friction ...	1251.22	58.237	0.842+	58.828	59.330	0.502 gain
9 Friction ...	1253.92	55.328	0.070+	55.118	55.678	0.560 gain
9 Radiation ...	0	55.528	0.148+	55.678	55.674	0.004 loss
10 Radiation ...	0	54.941	0.324-	54.614	54.620	0.006 gain
10 Friction ...	1257.96	54.985	0.085-	54.620	53.180	0.560 gain
11 Radiation ...	0	55.111	0.069+	55.180	55.180	0.000
11 Friction ...	1258.59	55.229	0.227+	55.180	55.733	0.553 gain
12 Friction ...	1258.71	55.433	0.238+	55.388	55.954	0.566 gain
12 Radiation ...	0	55.687	0.265+	55.954	55.950	0.004 loss
13 Friction ...	1257.91	55.677	0.542+	55.950	56.488	0.538 gain
13 Radiation ...	0	55.674	0.800+	56.488	56.461	0.027 loss
14 Radiation ...	0	55.579	0.583-	54.987	55.006	0.019 gain
14 Friction ...	1259.69	55.864	0.568-	55.006	55.587	0.581 gain
15 Radiation ...	0	56.047	0.448-	55.587	55.612	0.025 gain
15 Friction ...	1259.89	56.182	0.279-	55.612	56.195	0.583 gain
16 Friction ...	1259.64	55.368	0.099+	55.195	55.739	0.544 gain
16 Radiation ...	0	55.483	0.250+	55.739	55.728	0.011 loss
17 Friction ...	1259.64	55.498	0.499+	55.728	56.266	0.538 gain
17 Radiation ...	0	55.541	0.709+	56.266	56.235	0.031 loss
18 Radiation ...	0	56.769	1.512-	55.230	55.284	0.054 gain
18 Friction ...	1260.17	56.906	1.372-	55.284	55.905	0.621 gain
19 Radiation ...	0	60.058	1.763-	58.257	58.334	0.077 gain
19 Friction ...	1262.24	60.112	1.450-	58.334	58.990	0.656 gain
20 Radiation ...	0	60.567	1.542-	58.990	59.000	0.010 gain
20 Friction ...	1261.94	60.611	1.239-	59.000	59.655	0.655 gain
21 Friction ...	1264.07	58.654	0.321-	58.650	58.616	0.034 loss
21 Radiation ...	0	58.627	0.018-	58.616	58.603	0.013 loss
22 Friction ...	1262.97	58.631	0.243+	58.603	59.145	0.542 gain
22 Radiation ...	0	58.624	0.505+	59.145	59.114	0.031 loss
1	2	3	4	5	6	7

x 2

cles of bodies. It is easy to understand how the mechanical force expended in the condensation of air may be communicated to these particles so as to increase the rapidity of their motion, and thus may produce the phenomenon of increase of temperature. (Joule 1845, p. 381; 1884, p. 186)

That, in retrospect is very close to the often heard simplified contemporary statement that thermal energy is basically the kinetic energy associated to the vibrations of the atoms of a body. Joule then discussed his results and linked them to results he obtained in previous experiments; and to the works of Rumford, Humphry Davy (1778–1829) and James David Forbes (1809–1868):

The mean of the last three, which I take as least liable to error, is 798 lb., a result so near 838 lb., the equivalent which I deduced from my magnetical experiments, as to confirm, in a remarkable manner, the above explanation of the phenomena. [...] The beautiful idea of Davy, that the heat of elastic fluids depends partly upon a motion of particles round their axes, has not I think hitherto received the attention it deserves. (*Ibidem*; 1884, p. 187)

About this, Robert Fox wrote:

Joule still needed to prove beyond any doubt that the heat arose solely from the work done. [...] An experiment in which expansion occurred without the performance of external work would provide a crucial test. If Joule was right, no temperature change would be observed. [...] Since the expansion was into a vacuum, no net external work was done and Joule observed, to his undoubted satisfaction, that the temperature of the surrounding water remained unchanged. (Fox 1969, p. 90)

As more and more *natural philosophers* were gathering empirical data, advancing theories and conversing, the discovery and formulation of the principle of conservation of energy was indeed brewing:

It is the opinion of many philosophers that the mechanical power of the steam-engine arises simply from the passage of heat from a hot to a cold body, no heat being necessarily lost during transfer. This view has been adopted by Mr. Clapeyron in a very able theoretical paper, of which there is a translation in the 3rd part of Taylor's Scientific Memoirs. This philosopher agrees with Mr. Carnot in referring the power to *vis viva* developed by the caloric contained by the vapour in its passage from the temperature of the boiler to that of the condenser. I conceive that this theory, however ingenious, is opposed to the recognized principles of philosophy, because it leads to the conclusion that *vis viva* may be destroyed [...] Believing that the power to destroy belongs to the Creator alone, I entirely coincide with Roget and Faraday in the opinion that any theory which, when carried out, demands the annihilation of force, is necessarily erroneous. (Joule 1845, pp. 382–383; 1884, pp. 188–189).

Finally, Joule concluded that “[...] the steam, while expanding in the cylinder, loses heat in quantity exactly proportional to the mechanical force which it communicates by means of the piston, and that on the condensation of the steam, the heat thus converted into power is not given back.” (*Ibidem*). All Joule's experiments so far and the “so near” (*Ivi*, p. 387; 1884, p. 187) results he obtained, culminated in what eventually led him to earn the Royal Medal in 1852, “For his paper on the mechanical equivalent of heat”. In this experiment which is also commonly referred to as *Joule's paddle-wheel experiment*, Joule explicitly mentioned his conviction that heat was related to electricity, chemical action and mechanical force:

Results so closely coinciding with one another, and with those previously derived from experiments with elastic fluids and the electro-magnetic machine, left no doubt on my mind as to the existence of an equivalent relation between force and heat; but still it appeared of the highest importance to obtain that relation with still greater accuracy. This I have attempted in the present paper. (Joule 1849, p. 64; 1884, p. 302)

In the end, Joule drew the two following conclusions:

1st. That the quantity of heat produced by the friction of bodies, whether solid or liquid, is always proportional to the quantity of force expended. And, 2nd. That the quantity of heat capable of increasing the temperature of a pound of water (weighed in vacuo, and taken at between 55° and 60°) by 1° Fahr., requires for its evolution the expenditure of a mechanical force represented by the fall of 772 lbs. through the space of one foot.⁶Oak Field, near Manchester, June 4th, 1849. (Joule 1849, p. 82; 1884, p. 328).

⁶ A third proposition, suppressed in accordance with the wish of the Committee to whom the paper was referred, stated that friction consisted in the conversion of mechanical power into heat.

This last experiment is probably his most famous experiment involving the forthcoming principle of conservation of energy.

4 The Papers of this Special Issue

Thanks to cutting-edge researches done by prominent specialists this collection of contributions represents an outstanding amount of work and thorough analyses of the interdisciplinary environment in constant evolution that is history of science (physics, mathematics, chemistry), applied science and technology, technical education, and this, always with great respect towards historical context and Nature of Science in mind.

Joseph Agassi's (Israel and Canada) *Foreword* brilliantly paints a critical picture of how Science Education is related to (and) impacted by traditional education and the corresponding theories in a synthetic and effective way. He made the distinction between “education proper” and “instruction proper” and—starting from this base point—he analysed the actual bearings of education and how it is realized in public education: e.g., free school model, its limits and benefits and how it compares with traditional schools. The author pointed out that there is a lack of follow up studies comparing pupils from each of these models but that the data so far seems to indicate that the two school models are a priori equivalent, and thus that the free schools should be preferred. The reason for this being that according to him, if both models of school lead to comparable academic results, the free school model nevertheless has additional benefits that are not part of the academic evaluation. Such benefits include but are not limited to a stronger inclination to develop pupils' independence, the actual practice of democracy which ironically is done rather undemocratically in the traditional system; or more specifically regarding science education, he concluded that avoiding science teachers pulling rabbits out of top hats by forcing pupils in learning situations, either authoritatively or with the discovery method had been shown to lead to desirable outcomes. We thank you very much Joseph for this distinguished and authority essay.

In “Joule's 19th Century Energy Conservation Meta-Law and the 20th Century Physics (Quantum Mechanics and General Relativity): 21st Century Analysis” **Vladik Kreinovich (U.S.A) and Olga Kosheleva (U.S.A.)** intelligently showed how Joule's discovery of the Energy Conservation Law became the first “meta-law” and thus acted both as a beacon of light for later discoveries and a discriminant factor restricting physical theories. Throughout this paper, the authors investigate the implications of taking into account free will into physical theories, classical (pre-quantum), quantum and finally in general relativity and how this additional piece of information impacts the conservation of energy and its physical meaning. Even if along their formal mathematical investigations the inclusion of free will seems at first to be in contradiction with energy conservation, the authors managed to show that Joule's principle is actually still valid for all physical theories; for instance, the authors show how the apparent disappearance of energy is actually linked to space–time curvature.

In “Introducing Joule's paddle wheel experiment in the teaching of energy: why and how?” **Manuel Bächtold (France)** accurately discusses the benefits offered by the replication of historical experiment. In particular, he focuses on Joule's paddle-wheel experiment and how it allows three main approaches in order to teach the concept of energy: in terms of equivalence, in terms of energy change, and in terms of energy transformation. After describing these approaches and reporting their respective strengths and weaknesses due

to how they differ both from the treatment of the experiment (phenomenological, qualitative, quantitative...), and from the main focus on the concept to teach (concept of energy vs. conservation of energy vs. transformation of energy), the author analysed the potential contradictions or complementarity of these approaches. This led him to a proposal and to discuss the advantages to introduce energy as a unifying quantity; which could, at the same time, allow the students to build “bridges” or connexions between different fields of physics (namely mechanics and thermodynamics).

In “Science Outside Academies. An Italian Case of ‘Scientific Mediation’. From Joule’s seminal experience to Lucio Lombardo Radice’s contemporary attempt”, **Fabio Lusito (Italy)**, by means of a good eloquentia, discussed the possibility of “making” science outside of the standard academic paths and the necessity for science diffusion and popularization. The author divided his paper into two main parts. The first one concerns historical aspect of science outside academies, including the rise of science popularization—with a particular focus on Joule and Faraday’s experiences on the matter—and sets the historical scene and development of scientific mediation. The second one being specifically about Lucio Lombardo Radice who was a scientist (and politician) well versed into scientific mediation and depicts the efforts and convictions of a man who never stopped trying to transmit his love for science and educate the broader audiences possible.

In “Conservation of Energy: Missing Features in Its Nature and Justification and Why They Matter”, **Brian Pitts (U.K.)** explores in detail the history of conservation laws in physical theories from the late 17th century to our modern understanding: from Cartesian mental causation, the works of Leibniz, Joule, Einstein, Noether to the 2010s. The main focal points being the historical, philosophical and physical aspects of uniformity of nature, locality, symmetries. This panoramic analysis of one of the most important concepts in Physics leading to natural questions for the Science Education about the Teaching–Learning of conservation laws. In particular, the author addresses the importance of this issue for secondary school science education and formulated a number of suggestions for the reformation of secondary school teaching about the conservation of energy that do not necessarily include mathematics otherwise too advanced.

In “Joule’s Experiments on the Heat Evolved by Metallic Conductors of Electricity”, **Roberto de Andrade Martins (Brazil)** focused on one of Joule’s most famous scientific contributions on the laws of heat production by electric currents in conductors. The general aim is to explore—in detail and critically—how this experiment was apprehended both by Joule and the scientific community of the time. The author produced an historical analysis and used case studies within Nature of Science. He remarked that doing science has its challenges, which are not only technical but also humane and that science is an everlasting collaborative endeavour in which all relevant contributions are welcome—even though not all are remembered despite the value they added.

In “Fundamental Questions about the Energy Concept”, **Ricardo Coelho (Portugal)**—in order to investigate the reasons behind the difficulties of understanding what energy is—authoritatively examined the historical-physical context in which the roots of the problems of defining and identifying energy have developed. In the middle of the 19th century, the different views of the scientists of the time led them to propose and develop several experiments in order to tackle the problem of heat, each experiment testing various suppositions (heat as a substance, heat as motion or heat as a magnitude expressed in mechanical units). The mechanical equivalent of heat found by Joule was a huge turning point from which the concept of energy took off; however, despite its ubiquitous use in Physics, the struggle to understand what energy is still going on nowadays even if progress has been made because of the very nature of the problem, which has no laboratorial solution.

In “Joule’s Experiment As a Turning Point for the Historical Passage from Baconian Science to an Alternative Theory to the Newtonian One”, **Antonino Drago (Italy)** revisited the paradigm shift caused by the development of thermodynamics with respect to Joule’s paddle-wheel experiment. He intelligently analysed how that provoked a revolution by shaking the foundations of theoretical physics. The re-examination of the events and new approaches for doing science had tremendous implications for the change that occurred at that time, even more so considering, not only new approaches, but the diversity of theories that were completely different in essence. In particular, the author focuses on how the formalization and the innovations brought by Joule’s way of doing science triggered this paradigm shift through another way of organizing theories; and therefore impacted science and, of course, history of science.

In “Historical Foundations of Physics & Applied Technology as Dynamic Frameworks in Pre-Service STEM”, **Raffaele Pisano (France), Philippe Vincent (France), Kosta Dolenc (Slovenia) and Mateja Ploj Vrtič (Slovenia)** explore—in detail—recent results within historical and Nature of Science approaches in favour of pre-service teachers in Science, Technology, Engineering and Mathematics. They make several suggestions for the Teaching–Learning of scientific knowledge including NoS, for in order as both innovative pedagogy and to raise the level of teaching–learning. A number of historical experiments can be used for lectures in diverse scientific fields, and Joule’s experiments are anchored at one of the most important turning points in the history of physics very well documented. For, the authors consider them as a gold mine for teaching as in conjunction with modern methods and technologies, they also allow for a deeper multilevel understanding of the physical phenomena involved.

The papers of this IDTC special issue have been independently peer-refereed and followed *Foundations of Science* (Springer) policy. The authors’ contributions have been presented in alphabetical order. The guest editors have respected individual authors’ different ideas and historical, epistemological and educational/teaching accounts. Therefore, the editors are not responsible for the contents. Each of the eminent authors is responsible for his/her/their own opinions, which should be regarded as personal scientific and experienced background. The authors are also univocally responsible for images, reprints, quotations, acknowledgments, and all related permissions/approvals displayed/not displayed in their papers.

Acknowledgments The genesis of this *Special Issue* relies upon studies in history of science (physics, mathematics, chemistry), applied science and technology, technical education, within detailed historical contexts and nature of science. We warmly express our appreciation—and—pleasant gratitude to the libraries; and contributing authors for their activities to produce papers of interest and of high quality. We also address our acknowledgments to Diederik Aerts & Sandro Sozzo (Editors in-Chief) and their staff for their good job—and—positive reception of our project to publish a special issue on *James Joule’s bicentenary* in the prestigious *Foundations of Science*.

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