21

ENERGY

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Between Isaac Newton and Albert Einstein no development in physics is more significant than the replacement of the concept of force by the concept of work. Historians usually argue that the *energy* revolution occurred around 1850, but that interpretation fails to recognise that the concept of work remained the essential measure of energy until energy acquired a status independent of mechanics late in the nineteenth century.

As early as 1854, William Thomson (later Lord Kelvin, 1824–1907) told the British Association for the Advancement of Science that James Prescott Joule's discovery of the conversion of work into heat by fluid friction in 1843 had 'led to the greatest reform that physical science has experienced since the days of Newton'. And in 1908, Sir Joseph Larmor, Lucasian Professor of Mathematics at Cambridge, regarded energy as the most far-reaching achievement of nineteenth-century physical science: 'This doctrine has not only furnished a standard of industrial values which has enabled mechanical power . . . to be measured with scientific precision as a commercial asset; it has also, in its other aspect of the continual dissipation of available energy, created the doctrine of inorganic evolution and changed our conceptions of the material universe'.[1] Such remarks are symptomatic of a fundamental reformulation of physical science which took place after 1840 and which redefined physics itself in the second half of the century as the study of energy and its transformations.

1. 'FORCE' VERSUS 'WORK'

The concept of force has a long history. In his *Philosophiae Naturalis Principia Mathematica* (*Mathematical Principles of Natural Philosophy*, 1687), Newton (1642–1727) expressed the wish that we could 'derive the rest of the phaenomena of Nature by the same kind of reasoning from mechanical principles [as in the case of gravitation], for I am induced by many reasons to suspect that they may all depend upon certain forces by which the particles of bodies . . . are either mutually impelled towards one another . . . or are repelled and recede from one another'.[2] Many subsequent writers followed Newton's prescription and attempted to account for diverse phenomena by combinations of attractive and repulsive forces between particles or point atoms. While most attempts were qualitative and speculative, some, notably Coulomb's formulation of an inverse square law of electrical attraction, were numerically-based.

In the early nineteenth century, Pierre-Simon Laplace's (1749–1827) programme for the reduction of all physical phenomena to the action of inverse square forces between point atoms marked the high tide of force physics. (See art. 18.) Unlike Newton's infinitely hard atoms, Laplace's atoms could never collide, not only because they were mere points but also because they repelled one another with forces that increased as the distance diminished. Hence, while Newton's inelastic atoms lost motion at every collision, Laplace's atoms could never lose *vis viva* which he defined as mass times the square of the velocity. Laplace's universe had no need of Newton's God who acted continually to replenish motion in a world which would otherwise run down.

Laplace's reductionist programme was comprehensive. He announced that:

> . . . the phenomena of expansion, heat, and vibrational motion in gases are explained in terms of attractive and repulsive forces which act only over insensible distances . . . All terrestrial phenomena depend on forces of this kind, just as celestial phenomena depend on universal gravitation. It seems to me that the study of these forces should now be the chief goal of mathematical philosophy.[3]

With his French followers, he carried this programme into most branches of physics. Siméon-Denis Poisson (1781–1840), in particular, developed the mathematical theories of heat and electricity (electrostatics). A proper derivation of the equations of heat conduction, for example, began with an explicit model of the relation between ponderable molecules and caloric fluid in a solid. From a complex and speculative picture, Poisson extracted by rigorous but laborious mathematical methods the general equation for the motion of heat. Again, his theory of electricity was a theory of action at a distance between point masses of electrical fluid, an approach at once rigorous and complex, leading to equations insoluble for all but the simplest cases.

By contrast, the approach of Joseph Fourier (1768–1830) marked a decisive shift away from the force physics of the Laplacians. He continued the Laplacian priority on mathematical analysis, but at a practical rather than at a hypothetical level. Fourier therefore treated heat conduction as though it were a phenomenon of continuous flow, without regard to its true physical nature. His technique brought the power of mathematical analysis to bear directly on empirical laws without any appeal to microscopic models of the Laplacian kind. His theory of heat was essentially macroscopic, geometrical and practical. Thus against Poisson's view from *inside* the machine, so to speak, Fourier set the engineer's view from *outside* the machine.

The development of a strong tradition of theoretical engineering in France, especially following the Revolution, greatly strengthened the trend away from centrally-directed forces, as exemplified in the Laplacian programme. In particular, Lazare Carnot and Gaspard Monge, key figures behind the new Ecole Polytechnique, maintained close contact with engineering needs and emphasised the mechanics of machines and geometrical analysis in their textbooks and teaching. As early as 1782, Carnot's *Essai sur les machines en général* had begun to give the concept of 'work' (force times distance) priority over force in dynamics. Under various names such as 'mechanical power' (John Smeaton) or simple 'effect' (James Watt), work was the basic measure of engine achievement (weight times height) and derived from those practical engineers of early industrialisation who required a useful comparison of the relative performances of water, wind, animal and steam sources of power. Work did not, in general, appear as an independent concept in the abstract dynamical literature where the principle of conservation of *vis viva* occupied an important position.

The generation after Carnot and Monge transformed engineering mechanics into a new science of work. In the period 1819–1839 work terms such as *quantité de travail* (Coriolis) or *travail mécanique* (Poncelet) were introduced, *vis viva* redefined as $\frac{1}{2}mv^2$ such that work achieved and retained priority over the old mv^2, and the equation between work and half *vis viva* explicitly formulated. Largely as a result of the pressing needs of French industry to match Britain after 1815, this new generation did not concern itself with trial-and-error methods but with improving industry through a better understanding of the principles of machines. These practically-orientated theories of machines came much closer to Fourier's mathematical physics than to the abstract force physics of Laplace.

Sadi Carnot's *Reflexions sur la puissance motrice du feu* (1824) belongs to this generation of French theoretical engineers. Impressed by the fuel economy of Woolf's 'high pressure' compound steam engine compared to 'low pressure' Watt engines, Carnot (1796–1832) aimed to explain this relative economy and to consider whether further improvements were possible. His answer was that the motive power produced by heat engines depended only on the temperature difference between boiler and condenser and not on the working substance (steam, air, etc.) employed. In other words, the larger the temperature difference, the greater the work produced by a given quantity of heat. He reasoned that no engine could be more efficient than a perfectly reversible one in which the motive power produced by a quantity of heat falling between two temperatures could be employed to raise the same quantity of heat to its original temperature. Violation of this principle would yield work for nothing. He therefore set a theoretical limit to the possible improvements to heat engines operating between fixed temperatures.

Though Carnot's reasoning later formed one of the twin pillars of energy physics and thermodynamics, his text was almost wholly ignored by his French contemporaries. Nevertheless, one engineer, Emile Clapeyron, published an exposition of Carnot's views, in analytical form, in the *Journal de l'Ecole Polytechnique* (1834). Significantly, this paper was translated for a British publication in 1837 and for a German scientific journal in 1843. In this way, Carnot's ideas were introduced to most of the principal characters in the formulation of energy physics: Joule, Thomson, W. J. M. Rankine, Hermann von Helmholtz and Rudolf Clausius.

To understand the reception of Carnot in Britain, and the concomitant development of energy or 'work' physics, we must consider briefly the industrial context. Especially from the 1830s, the expansion of railways and steamships accentuated the need for improved economy in the production of motive power. At the centre of the new industrial universe stood the rapidly-growing cities of Manchester and Glasgow. In Manchester, William Fairbairn's giant steam engine, boiler and locomotive building works provided tangible proof of the city's industrial progress, wealth and power through steam and iron. In Glasgow a similar trend towards heavy engineering was evident in the activities of the marine engine-builder Robert Napier who had laid the foundations for the spectacular growth from 1840 of iron and steam ship-building on the River Clyde. For these and other industrialists at the forefront of engineering progress, questions of economy could only be solved by an understanding of engineering and physical principles and not by the trial-and-error methods which permeated most of the older industries. This quest for economy thus involved feeding back the advances made by French textbook writers and their British successors into industrial practice.

Symptomatic of the trend was the rapid professionalisation of British academic engineering from 1840. In that year, the appointment of Lewis Gordon (1815–75) to the University of Glasgow marked the creation of the first British engineering chair. Gordon and his successor, Rankine, developed close links with scientifically-minded industrial chemists, engineers and reforming academics via the Glasgow Philosophical Society. In 1840–41 at Cambridge, William Whewell (1794–1866) and Robert Willis published their complementary engineering textbooks on *The Mechanics of Engineering* and *The Principles of Mechanism*. The appearance of these very practical texts for the use of both university students and students in colleges of engineering is all the more striking when set against the traditional academic concerns of the University of Cambridge.

Whewell's textbook explicitly adopted the term 'labouring force' from the French 'travail' employed by writers on industrial machines. Apart from being the first major British text to employ 'work' as central to mechanics, Whewell's use of the term 'labouring force' expressed his parallel interest in the science of political economy and its labour theory of value. 'Labouring force is the labour that we pay for', Whewell explained, and went on to develop the economic theme by distinguishing work done by machines (equivalent to the wages of labour) from work accumulated in storehouses such as reservoirs of water or flywheels (equivalent to capital).[4]

Gordon was particularly concerned with the correct measure of work. Listing a variety of British and French synonyms, he chose 'mechanical effect', from the German 'mechanische Wirkung', which virtually coincided with Watt's practical employment of 'effect', and which was the term most often used by Thomson and his circle until their more frequent usage of 'energy' from the early 1850s. With practical engineers very much in mind, Gordon emphasised that mechanical effect was correctly measured as 'the produce of the *effort* and the *distance through which it is exerted* which should be obtained directly from a dynamometer'.[5]

2. WILLIAM THOMSON AND THE NEW PHYSICS OF 'WORK'

William Thomson's education in Glasgow and Cambridge brought him into close contact with these engineering trends. But above all, the passionate engineering enthusiasms of his elder brother, James (1822–92), led him to place mechanical effect at the very centre of his physics. First as a pupil of Gordon's and later as an apprentice at Fairbairn's Thames shipbuilding and marine engineering subsidiary, James's concern with designs for more economical marine steam engines and water wheels was all-pervasive. As early as 1844 he initiated discussion with William of the Carnot-Clapeyron theory of the motive power of heat. Throughout these discussions, the production of mechanical effect and its efficient use formed the central theme. For example, they were concerned with the problems of losses of mechanical effect in water spilling into canal locks and in steam engines. These issues would be vital to William's reception of Joule's claims presented at the 1847 meeting of the British Association.

Meanwhile, William had begun to reformulate mathematical physics. The attempt marked a major step in the transition from force physics to energy-field physics. In his earliest papers, he had frequently drawn a mathematical analogy between electricity and heat. In 1841, for instance, he had compared Poisson's theory of electricity (based on action at a distance force) with Fourier's theory of heat conduction (based on continuous and hence conserved fluid flow) and shown that the distribution of lines of electrical force in space obeyed the same equation as the distribution of heat flux in a homogeneous conductor. Electricity, like heat, he treated not as a fluid substance, but as a state of intensity of a body. Thus the high temperature of a steam boiler corresponded to a state of intensity of heat, and the low temperature of the condenser to a state of diffusion of heat.

Not until 1845, however, did Thomson begin to compare a charged electrostatic system with a steam engine.[6] His approach developed fully while he worked during the spring of 1845 in Victor Regnault's physical laboratory. Regnault was then carrying out for the French government precise quantitative experiments on high pressure steam aimed at improving the economy of steam engines. Thomson wanted an expression for the total force (ponderomotive force) between two electrified conducting spheres which would allow easy comparison with experimental measurements. He could have conceived the calculation as a sum of forces acting at a distance between point particles of electrical fluid on both spheres. Such a calculation required, however, a complicated double integral over the two spheres and presupposed knowledge of the mutually influencing electrical distributions. Instead, he recognised that this problem was of the same kind as the problem of work derived from a steam engine.

In a letter of 1844 James had been concerned with the capacity for work of a steam engine, a capacity which derived from the *tendency* of the system towards its lowest level of mechanical effect (the sea, for example). William considered the meaning of Carl Freidrich Gauss's (1777–1855) minimised function for a proof of existence and uniqueness of electrical distributions on conducting surfaces. He realised that the function could be interpreted as the mechanical effect contained in the system, and that therefore the electrical distribution would be such as to reach the lowest level of total mechanical effect, as with water and other mechanical systems. For the two spheres problem, then, the ponderomotive force between them was the tendency of the system to reach its lowest state of mechanical effect.

Thomson's new view, centred on the concept of mechanical effect, expressed the work expended or absorbed by an electrical system in exactly the same way as a waterfall or steam engine, with electrical potential analogous to the height of a waterfall or temperature difference between boiler and condenser, and quantity of electricity analogous to mass of water or quantity of heat. Total force became total work contained in the system, with attention focused not on summing over elementary forces among the parts but on the work entering or leaving the system. Total mechanical effect thus became a potential (soon to be potential energy) for the gross forces exerted by the system.

Thomson's deployment of these analogies began a process which changed mathematical physics. Work became the central concept of physical theory. Statics became a special case of dynamics. Within two years, he was employing the new conception over a wide range of phenomena. For example, he derived the total force on a piece of soft iron placed in a magnetic field as the tendency for the mechanical effect in the entire field to attain its lowest level. Mechanical effect was now located *in the field* rather than in the forces exerted on magnetic matter. Here he advanced the mathematical basis of field theory. (See art. 22, sect. 2.)

Equally important was his new conception of measuring quantities or agents such as electricity and heat by their mechanical effect, independently of materials, arrangements and other variables; the work done by an electrical or heat engine gave an absolute measure of physical quantities. Thomson now began to develop a theory of absolute measurements in terms of the behaviour of physical systems as engines, the best-known example being his absolute scale of temperature developed in 1847–48. His concern with absolute electrical measurements also provided the foundation for the British Association's work, from 1861, on electrical units. Such concerns were vital to the development of nascent electrical industries of telegraphy and power.

Thomson's new perspective, then, originated within the context of the Carnot-Clapeyron theory of heat engines in which the passage of heat from a hot to a cold body produced mechancial power (work or *vis viva*). In 1847, however, he met Joule (1818–89) for the first time and discovered that three years earlier Joule had mounted a strong attack on the Carnot-Clapeyron theory. Joule objected to the implication that by an improper disposition of the engine (leading to waste by conduction or collision, for example), the *vis viva* would 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'.[7] Joule's own theory substituted for the temperature difference a straightforward conversion of the heat (contained in the steam expanding in the cylinder of a steam engine) into an equivalent quantity of mechanical power.

The Thomsons were very sceptical of Joule's claim for the *mutual* conversion of heat and work. Their careful study of his papers seemed to show that Joule's experimental researches had only demonstrated the conversion of mechanical effect into heat. His measurements offered a resolution to the problem of 'loss' or 'waste' which had troubled the brothers for some years, but his major claim to displace the Carnot theory with the conversion of heat into work remained unacceptable to them.

Apart from this disagreement over the recoverability of mechanical effect 'lost' as heat, however, much about Joule's perspective appealed to the Thomsons. They shared his engineering interests, his quest for economy and his enthusiasm for accurate quantitiative measurement. They certainly shared his theology of nature whereby an omnipotent God created and held in being a universe whose basic building blocks (matter and other agencies such as 'force' or 'energy' discovered by experiment) could not be increased, annihilated, or otherwise altered by any human or natural agency. Such a metaphysical belief was one to which all Christians, irrespective of denomination or status, had to give allegiance. It made possible the wide acceptance of the new conservation of energy doctrine on account of its perceived non-sectarian, non-speculative and non-hypothetical character. Thus William entirely admitted Joule's specific objection to the Carnot-Clapeyron theory. The consensus illustrates the importance of a shared metaphysics in rendering a doctrine acceptable. For Thomson, as for Joule, energy (measured as mechanical effect) had to be conserved: 'Nothing can be lost in the operations of nature – no energy can be destroyed'. In this 1849 footnote to his exposition of Carnot's theory, Thomson introduced the term 'energy' into mathematical physics.[8]

Committed to Carnot's theory and to a concomitant view of heat as a state of intensity (rather than to material caloric as was often assumed), Thomson was, however, still not prepared to accept Joule's preference for a mechanical (soon called dynamical) theory of heat. Joule's hypotheses on the nature of matter and its properties were avowedly mechanical. In 1843, for example, he made clear that if 'we consider heat not as a *substance*, but as a state of vibration, there appears to be no reason why it should not be induced by an action of a simply mechanical character'. Here he did not attempt to establish a dynamical theory of heat from the experimental results; rather, he used the general theory (heat as a state of vibration) to render these results plausible or intelligible. In 1844, however, he reversed his argument. The near constancy of the mechancial equivalent of heat afford 'a new and, to my mind, powerful argument in favour of the dynamical theory of heat'. He proceeded to construct a tentative model involving atmospheres of electricity revolving very rapidly (and hence possessing *vis viva*) around atoms.[9]

When in 1848 Thomson acquired from Lewis Gordon a copy of the very rare Carnot text, he was uniquely placed to offer an up-to-date exposition of Carnot's theory in the light of the problems raised by Joule. As Thomson presented Carnot's theory in his 1849 'Account', the logic had four stages:

1. The heat in a body is a state function (i.e. in any cyclic process the change in heat content is zero).
2. Any work obtained from a cyclic change of state thus derives from the only change that can occur in such a cycle: namely, transfer of heat (without loss) from high to low temperature.
3. Application of (2) to a reversible process, together with denial of perpetual motion, yields Carnot's criterion for a perfect engine: no engine is more efficient than a reversible one.
4. From (3) it follows that the maximum efficiency obtainable from any engine operating between heat reservoirs at different temperatures is a function of those temperatures (Carnot's function).[10]

Familiar with Clapeyron's memoir, with Joule's results, and now with Thomson's latest analysis, the German theoretical physicist Rudolf Clausius (1822–88) produced in 1850 the first reconciliation of Joule and Carnot. Accepting a general mechanical theory of heat (that heat was *vis viva*) and hence Joule's view of the convertibility of heat and work, Clausius retained that part of

Carnot's theory which demanded a transfer of heat from high to low temperature when work is produced. Under the new view, then, a portion of the original heat was converted into work according to the mechanical equivalent of heat, the remainder descending to the lower temperature. Having abandoned (1) and part of (2) above, Clausius attempted to demonstrate (3) by reasoning that if it were false, then 'it would be possible, without any expenditure of force or any other change, to transfer as much heat as we please from a cold to a hot body, and this is not in accord with the other relations of heat, since it always shows a tendency to equalise temperature differences and therefore to pass from hotter to colder bodies'.[11]

Thomson had also moved towards a resolution. In 1851 he laid down two fundamental propositions, the first a statement of Joule's proposition of the mutual equivalence of work and heat, and the second a statement of Carnot's criterion for a perfect engine (3). His final acceptance of Joule's proposition rested primarily neither on experiment nor on Joule's arguments but on resolving the problem of the irrecoverability of mechanical effect lost as heat. He now believed that work 'is *lost to man* irrecoverably though *not lost in the material world*'. Thus although 'no destruction of energy can take place in the material world without an act of power possessed only by the supreme ruler, yet transformations take place which remove irrecoverably from the control of man sources of power which . . . might have been rendered available'.[12] In other words, God alone could create or destroy energy (i.e. energy was conserved) but men could make use of transformations of energy, for example in water wheels or steam engines.

Thomson, then, accepted as a fundamental principle what he soon termed the universal dissipation of mechanical energy. Work dissipated as heat would be irrecoverable to man; to deny this principle would imply that we could produce mechanical effect by cooling the material world with no limit except the total loss of heat from the world. This reasoning provided the basis for Kelvin's 'second law of thermodynamics': 'it is impossible, by means of inanimate material agency, to derive mechanical effect from any portion of matter by cooling it below the temperature of the coldest of the surrounding objects',[13] a statement which Thomson used to demonstrate (3) above. Having resolved the recoverability issue, he quickly adopted the dynamical theory of heat, making it the foundation of Joule's proposition of mutual equivalence which replaced (1) above.

With Thomson's paper 'On a universal tendency in nature to the dissipation of mechanical energy' (1852), the energy synthesis reached a wide audience. There Thomson made explicit the dual principles of conservation and dissipation of energy: 'as it is most certain that Creative Power alone can either call into existence or annihilate mechanical energy, the 'waste' referred to cannot be annihilation, but must be some transformation of energy'.[14] In this short paper published in the *Philosophical Magazine*, the new term 'energy' achieved prominence for the first time. It was no longer a mere footnote; instead the shared theology of nature emphasised the primary status of energy. Here the dynamical theory of heat, and with it a whole programme of dynamical (matter-in-motion) explanation, went unquestioned. And here too, the universal, cosmological primacy of the energy laws opened up new questions about the origins, progress and destiny of the solar system and its inhabitants.

Thomson and others, such as Hermann von Helmholtz (1821–94) and Julius Robert Mayer (1814–78), soon considered the consequences of the energy laws for traditional accounts of the sun's heat, the great source for most of the mechanical effect on earth. In the 1850s, Thomson argued that the sun's energy, too great to be supplied by chemical means or by a mere molten mass cooling, was probably provided by vast quantities of meteors orbiting around the sun but inside the earth's orbit. Retarded in their orbits by an etherial medium, the meteors would progressively descend or spiral towards the sun's surface in a cosmic vortex analogous to James Thomson's vortex turbines (horizontal waterwheels). The meteors would generate immense quantities of heat energy as they vaporised by friction. In the 1860s, however, he adopted instead Helmholtz's version of the sun's heat whereby contraction of the body of the sun released immense quantities of heat over long periods. Either way, the sun's heat was held to be finite and calculable, making possible order-of-magnitude estimates of the limited past and future age of the sun. Thomson made similar estimates for the earth's age based on Fourier's conduction law applied to a cooling mass. The limited time-scale of about 100 million years (later reduced) posed problems for the much longer time demanded by Charles Darwin's new theory of evolution by natural selection (1859). But the new cosmology was itself evolutionary, making claims to trace the history of the solar system from origins to endings via the energy laws. (See art. 20.)

While Thomson, Rankine, Helmholtz, Clausius and many others developed specific experimental and theoretical consequences of the energy laws in most areas of cosmology, physics and engineering, the nineteenth-century programme of energy physics received its most celebrated embodiment in Thomson and Peter Guthrie Tait's *Treatise on Natural Philosophy* (1867). Originally intended to treat all branches of physics, the *Treatise* was limited to mechanics. Its approach was nevertheless radical. Taking statics to be derivative from dynamics, it aimed to interpret Newton's third law (action–reaction) as conservation of energy, with 'action' viewed as rate of working. Fundamental to this work-based physics was the move to make extremum conditions, rather than point forces, the theoretical foundation of dynamics. The tendency of an entire system to move from one place to another in the most economical way would determine the forces and motions of the various parts of the system. Variational principles (least action, for example) thus played a central role in the new dynamics.

3. RIVAL CONNCEPTUALISATIONS OF ENERGY: MECHANICAL VERSUS NON-MECHANICAL THEORIES

In 1959 T. S. Kuhn named twelve European men of science and engineering 'who, within a short period of time, grasped for themselves essential parts of the concept of energy and its conservation'.[15] Recognition of this phenomenon of simultaneous discovery had already led to several bitter priority disputes (often in terms of national rivalries between Britain and Germany) in the second half of the nineteenth century. Yet a closer historical analysis of four of these 'pioneers' (Joule, Faraday, Mayer and Helmholtz) shows the very divergent nature of their conceptualisation, theories shaped by widely differing cultural perspectives ranging from Manchester engineering to German metaphysics. Only after the energy synthesis of Thomson, therefore, did the issue of simultaneous discovery arise.

Just as James Thomson devoted much time to researching and designing vortex turbines as an alternative to steam power, Joule's researches in Manchester began with attempts to design economical electro-magnetic engines. 'I can hardly doubt that electro-magnetism will ultimately be substituted for steam to propel machinery', Joule wrote in 1839.[16] Like James, Joule's major concern was with measuring and improving the economy of engines, although (unlike James) he never patented and marketed them. His published investigations from 1838 were based on work-related measurements. Lifting power (weight times unit height per unit time) yielded the criterion by which to judge the performance of an electro-magnet.

At a public lecture in 1841, Joule admitted disappointment with the performance of electro-magnetic engines: '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 zinc'. The comparison was so unfavourable that he confessed: '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 per lb. of coal'. In addition, the cost of the zinc and the battery fluids, compared to the price of coal, prevented 'the ordinary electro-magnetic engine from being useful for any but very peculiar purposes'.[17]

While some historians of science have seen Joule's subsequent research as a shift away from engineering and towards 'purer' science, others have interpreted Joule's researches in terms of a British matter theory tradition (especially the conversion and unity of natural powers) or in the context of the contemporary British chemical community. Support for each of these diverse perspectives can be found in Joule's texts. For example, Joule's evident familiarity with Faraday's recent electro-chemical and electro-magnetic investigations has been used to argue for Joule's and Faraday's common goals in terms of the conversion and unity of natural powers, electrochemistry, or experimental conversion processes.[18] However, a fundamental difference between Faraday and Joule explains why it was Joule, and not Faraday, who enunciated the mechanical equivalent of heat.

Foremost an experimental philosopher, whose lack of mathematical techniques has tended to obscure the often quantitative nature of his researches, Michael Faraday (1791–1867) nonetheless never attempted to measure exact conversion equivalents. As early as 1833 he stated that 'for a constant quantity of electricity, whatever the decomposing conductor may be . . . the amount of electro-chemical action is also a constant quantity, i.e. would always be equivalent to a standard chemical effect founded upon ordinary chemical affinity'.[19] Soon after, he discussed the use of a voltameter as a 'comparative standard, or even as a measurer' of electricity, while recognising also the importance of the voltameter as an 'absolute measurer' in terms of spatial units (the volume of gases evolved). Faraday's researches here and elsewhere show his use of comparative or relative quantitative measures; but his apparent unwillingness to make absolute ('mechanical') measures clearly differentiates his approach from Joule's. At a fundamental level, Faraday's concept of force was not a mechanical one and as such could not be quantified. Above all, he did not adopt the crucial concept of work which in the hands of Joule and Thomson provided the common measure and link for the numerous experimental conversion processes. In short, Faraday, who worked at the Royal Institution in London, lacked the engineering interests so entirely characteristic of Joule in Manchester and Thomson in Glasgow.

A vital clue to interpreting Joule throughout his researches, and not merely up to 1841, in terms of his engineering concerns, lies in the all-pervasive theme of heat, culminating in his 1843 phrase 'on the mechanical value of heat'. If the meaning of 'value' is again taken not merely in the quantitative but also in the economic sense, then Joule, after the 'almost despair' with his engine, did not turn to pure research, electrochemical in nature, and then from that research suddenly produce a series of papers on the mechanical equivalent of heat. Rather, his investigations throughout must be seen to involve a fundamental search for an understanding of the failure of his engine to match the economy of heat engines. That quest led him directly to the mechanical value of heat, that is, to the amount of work obtainable from a given quantity of heat. Significantly, Joule's primary interest lay with the mechanical value of heat, and not with the thermal value of mechanical work, the latter being Thomson's subsequent perception of the real achievement of Joule's experiments.

Joule's mechanical conceptions, which in general admitted only 'the existence and elementary properties of matter',[20] not only emphasise his distance from Faraday, but serve also to distance him from Mayer. Although Mayer's 'discovery' of the mechanical equivalent of heat has usually placed him among the 'pioneers' of energy, he did not accept a mechanical theory. In his view, the mere fact of interconversion did not justify taking any particular form of 'force' as fundamental. His refusal to accept a mechanical theory of heat may be understood in terms of his lingering adherence to (despite a professed rejection of) certain assumptions of the German metaphysical creed known as *Naturphilosophie*. For Mayer, force held a middle position between inert matter and *Geist* (which implied both mind and soul). All three categories (matter, force and soul) were by their nature indestructible, i.e. conserved. Forces expressed the rationality or causality of nature, especially in terms of relationship. Forces were not simply located in isolated matter (as for the Laplacians, for example), but arose only in the interrelations of matter. Although Mayer rejected the assumption of *Naturphilosophie* that we could construct the true system of nature by thought, he nevertheless seemed to employ empirical results primarily as confirmation of *a priori* conservation. This approach, together with his maintenance of force as some kind of substance, independent from matter but with equal status, rendered his arguments largely unacceptable to contemporary German physicists who had gone much further in their rejection of *Naturphilosophie*. For many empirically and practically-minded British physicists, Mayer's work remained largely within metaphysics, although Faraday's successor at the Royal Institution, John Tyndall, became a staunch defender of Mayer's claims to the discovery of energy conservation.

Helmholtz's famous 1847 memoir *Über die Erhaltung der Kraft* also illustrates the way in which different cultural perspectives shaped the central physical doctrines. His memoir brought together a German methaphysical perspective (from Kant) and French physics (from Laplace). Thus his philosophical introduction explained that 'the science whose object it is to comprehend nature must proceed from the assumption that it is comprehensible . . . Finally, therefore, we discover the problem of physical natural science to be, to refer natural phenomena back to unchangeable attractive and repulsive forces, whose intensity depends solely upon distance. The solvability of this problem is the condition of the complete comprehensibility of nature'.[21] This assumption of the rationality of nature (Kant) via the physics of point atoms and attractive and repulsive forces (Laplace) guaranteed conservation of *vis viva*. Furthermore, the assumption of the impossibility of perpetual motion, based on empirical considerations (Clapeyron and others), also supported conservation of *vis viva*.

Fundamental to Helmholtz's memoir was a relational view of force. Independently of Helmholtz, Mayer had neatly summed up this German perspective of *Verwandschaft* (relationship) in 1842: 'spatial separation of ponderable objects is a force'.[22] Helmholtz reasoned more specifically that if force did not always return to the same value for the same spatial relation, *vis viva* might be continuously produced from nothing, which would violate both the equality of cause and effect (the principle of sufficient reason) and the impossibility of perpetual motion. His arguments depended for their articulation on the Kantian distinction between quantity and intensity. For Helmholtz, in the realm of forces between point atoms, Newtonian moving force became the measure of the intensity of force, while the conserved quantity of force was measured by *vis viva* or potential or work. Thus the relation between two atoms at any instant possessed intensity (producing changes in spatial relation) and quantity (connecting the past history of the relation to its future).

Helmholtz's 1847 memoir, with its Kantian-Laplacian synthesis, was vastly different from Thomson's work-centred field physics developing in Britain at the same time. Helmholtz's assumptions related to German philosophy, French theoretical physics and German physiology (concerned especially with the elimination of all traces of *Geist*). Thomson's assumptions related to French engineering physics (Fourier and Carnot) and to British engineering (James Thomson and Joule). Nevertheless, the generally low profile of Helmholtz's metaphysics (relative to Mayer), and his mechanical reasoning – especially work as a measure of quantity of force – soon rendered his memoir acceptable to both German and British physicists.

Mechanical conceptualisations of energy, with work as its essential measure, dominated British and German physics in the second half of the nineteenth century. Towards the end of the century, however, a different perspective, which emphasised the independence of energy from mechanics, emerged in Germany. In the 1880s, Ernst Mach condemned the assumption that mechanics comprised the basis of all physical phenomena and argued instead for a phenomenological view in which sensations would constitute the real object of physical research. The principle of energy conservation served as an ideal: though mechanical theories had aided the formulation of the principle, once established it described only a wide range of facts concisely, directly and economically with no need for mechanical hypotheses.

The so-called 'Energeticist' school of physics also explicitly aimed to replace mechanics as the fundamental science. In 1890, Georg Helm attempted to derive the equations of motion from the conservation of energy and thus to subsume mechanics and its extensions under energetic foundations of physics. His ally Wilhelm Ostwald similarly wished to replace atomism in chemistry by energetics, and proposed a corresponding change from an absolute mechanical system of measurement to an energetic system in terms of energy, length and time. Overall, energetics aimed not to construct mechanical pictures but to connect measurable quantities with each other, a goal shared by Mach and later by the French physicist and philosopher Pierre Duhem whose critique of nineteenth-century British physics for its factory mentality is well known. But the energeticist school had formidable critics. Ludwig Boltzmann, for example, labelled energetics as mere classification, while Max Planck pointed out that it failed to distinguish between reversible and irreversible processes in nature. Of much more far-reaching consequences for the foundations of mathematical physics at the dawn of the new century were the questions posed by electromagnetism (see art. 22) in which energy considerations had, through the role of Thomson, Maxwell and their successors, come to play a major role.

NOTES

I am much indebted to Norton Wise for several of the interpretations included here, especially his insights into the central role of work in nineteenth-century British physics. This chapter draws extensively on material developed at length in our biographical study of Lord Kelvin.

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2. I. Newton, *Mathematical principles of natural philosophy*, trans. A. Motte, rev. F. Cajori (2 vols., Berkeley and Los Angeles, London, 1971), vol. 1, p. xviii.
3. P. S. Laplace, *Traité de mécanique céleste* (5 vols., Paris, 1799–1825), vol. 5, p. 99.
4. W. Whewell, *The mechanics of engineering* (Cambridge, 1841), pp. 146–57. Developed in M. N. Wise with the collaboration of C. Smith, 'Work and waste: political economy and natural philosophy in nineteenth-century Britain; *History of science* (forthcoming).
5. L. D. B. Gordon, 'On dynamometrical appartus; or, the measurement of the mechanical effect of moving powers', *Proceedings of the Philosophical Society of Glasgow*, 1(1841), 41–2; *A synopsis of lectures to be delivered. Session 1847–8* (Glasgow, 1847), p. 5.
6. This issue and related analogies are discussed more fully in M. N. Wise and C. Smith, 'Measurement, work and industry in Lord Kelvin's Britain', *Historical studies in the physical and biological sciences*, 17(1986), 147–73.
7. J. P. Joule, *The scientific papers of James Prescott Joule* (2 vols., London, 1887), vol. 1, pp. 188–9.
8. W. Thomson, 'On the mechancial antecedents . . .', *Mathematical and physical papers*, vol. 1, p. 118n.
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12. W. Thomson, *Preliminary draft for the 'Dynamical theory of heat'*, PA 128, Kelvin papers, Cambridge University Library.
13. W. Thomson. 'On the dynamical theory of heat; with numerical results deduced from Mr. Joule's "equivalent of a thermal unit" and M. Regnault's "observations on steam" ', *Mathematical and physical papers*, vol. 1, p. 179.
14. W. Thomson, 'On a universal tendency in nature to the dissipation of mechanical energy', ibid., vol. 1, p. 511.
15. T. S. Kuhn, 'Energy conservation as an example of simultaneous discovery', in M. Clagett (ed.), *Critical problems in the history of science* (Madison, 1959), pp. 321–56.
16. Joule, *Scientific papers*, vol. 1, p. 14.
17. Ibid., vol. 1, p. 48.
18. See respectively P. M. Heimann, 'Conversion of forces and the conservation of energy', *Centaurus*, 18(1974), 147–61; J. Forrester, 'Chemistry and the conservation of energy', *Studies in history and philosophy of science*, 6(1975), 273–313; T. S. Kuhn in Clagett, *Critical problems*, pp. 325–27. H. J. Steffens, *James Prescott Joule and the concept of energy* (New York, 1979), pp. 1–60 emphasises Joule's shift towards purer science.

19. M. Faraday, *Experimental researches in electricity* (3 vols., London, 1839–55), vol. 1, para. 505.
20. Joule, *Scientific papers*, vol. 1, p. 52.
21. Hermann Helmholtz, 'On the conservation of force; a physical memoir', in J. Tyndall and W. Francis (eds.), *Scientific memoirs. Natural philosophy* (London, 1853), pp. 114–62, on pp. 115–17.
22. Translated in M. N. Wise, 'German concepts of force, energy, and the electromagnetic ether: 1845–1880', in G. N. Cantor and M. J. S. Hodge (eds.), *Conceptions of ether: studies in the history of ether theories, 1740–1900* (Cambridge, 1981), p. 273.

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