CHAPTER 14

Sequel: Transforming Energy in the Late Nineteenth Century

> [Poynting's idea of continuity in the existence of energy is] an extension of the principle of the conservation of energy. The conservation of energy was satisfied by the *total quantity* remaining unaltered; there was no individuality about it: one form might die out, provided another form simultaneously appeared elsewhere in equal quantity. On the new plan we may label a bit of energy and trace its motion and change of form, just as we may ticket a piece of matter so as to identify it in other places under other conditions; and the route of the energy may be discussed with the same certainty that its existence was continuous as would be felt in discussing the route of some lost luggage which has turned up at a distant station in however battered and transformed a condition.
>
> *Oliver Lodge publicly endorses J.H. Poynting's interpretation of energy transfer in an electromagnetic field*[1]

From almost any subsequent vantage point Thomson and Tait's *Treatise on Natural Philosophy* (1867) and Clerk Maxwell's *Treatise on Electricity and Magnetism* (1873) appear as the most enduring embodiments of the science of energy. But these treatises, seemingly definitive, were in historical terms to prove highly malleable. This final chapter seeks to chart some of that malleability in the years following the death of James Clerk Maxwell. Indeed the rapid reinvention of Maxwell was symptomatic that the scientists of energy, overtaken by age and death, were no longer on an upward spiral of scientific credibility. As new groups vied with one another for scientific authority, the science of energy was to be reshaped beyond recognition.

By the 1880s the science of energy was fast slipping from the control of its original British promoters. Rankine and Maxwell had already gone from the scene. During the coming decade death would exact a further toll with the passing of Jenkin, Stewart and Joule. Thomson and Tait alone would continue to assert their

authority over physics in Britain. But against the new generations of physical scientists – theoretical and experimental physicists as well as physical chemists – Thomson especially began to look increasingly conservative, a survivor from a past era of natural philosophy.

In contrast the rising generations began to recast the energy doctrines for their own purposes. A self-styled British group of 'Maxwellians', comprising G.F. FitzGerald (1851–1901), Oliver Heaviside (1850–1925) and Oliver Lodge (1851–1940), reinterpreted Maxwell's *Treatise* for their own ends and in accordance with energy principles. But for them 'Maxwell was only half a Maxwellian', as Heaviside noted wryly in 1895 after he and his associates had wrought a transformation in Maxwell's original perspective.[2] Later 'Maxwellians' increasingly located energy in the field around an electrical conductor, tended to carry mechanical model building to extremes, and began to reify energy rather than regard it as mechanical energy or the capacity to do work. It was, above all, this fundamental link between matter and energy, whereby all energy was ultimately regarded as mechanical energy measured in terms of work done, that had characterized the scientists of energy.

William Thomson (by then Lord Kelvin), on the other hand, generally treated the newer electromagnetic views with unreserved contempt: 'It is mere nihilism, having no part or lot in Natural Philosophy, to be contented with two formulas for energy, electrostatic and electromagnetic, and to be happy with a vector and delighted with a page of symmetrical formulas'.[3] There was for him no substitute for dynamical theory, properly understood in conceivable and measurable terms. Although initially cautious about Maxwell's electromagnetic theory of light and always antagonistic to Maxwell's and Tait's seduction by vector notation, his personal, academic and cultural links to his protege strikingly contrast to his disagreements with the self-styled heirs to Maxwell's electromagnetic legacy.

These disagreements, however, appear relatively mild when set against the rise of the so-called 'Energeticist' school in Germany. This school marked a far more radical departure from the 'science of energy'. Led by the physical chemist Wilhelm Ostwald (1853–1922), the Energeticists rejected atomistic and other matter theories in favour of a universe of 'energy' extending from physics to society. Any remaining link between matter and energy had been decisively severed. The aged Lord Kelvin responded to this trend by writing disparagingly to Stokes's successor in the Lucasian chair of mathematics at Cambridge, Joseph Larmor, in 1906:

> Young persons who have grown up in scientific work within the last fifteen or twenty years seem to have forgotten that energy is not an absolute existence. Even the Germans laugh at the 'Energetikers'. I do not know if even Ostwald knows that energy is a capacity for doing work; and that work done implies mutual force between different parts of one body relatively movable, or between two bodies or two pieces of matter, or between two atoms of matter, or between an atom of matter and an electron, or, at the very least, between two electrons.[4]

Transforming Maxwell: the energy of the electromagnetic field

A striking characteristic of the 'Maxwellians' (FitzGerald, Lodge and Heaviside) was their distance from the British mathematical establishment represented in the University of Cambridge, most notably by the famous Mathematical Tripos. Cambridge regarded Maxwell's *Treatise* as a resource for abstruse mathematical problems, especially through the application of Lagrangian methods, rather than as a key to physical nature. The Maxwellians, however, directed their attention not to the applications of Lagrangian methods but to the distibution and flow of electromagnetic energy.[5]

FitzGerald's academic career centred on Trinity College Dublin, already celebrated for its association with the distinguished nineteenth-century Irish mathematicians and natural philosophers Sir William Rowan Hamilton (1805–65), Humphrey Lloyd (1800–81) and James MacCullagh (1809–47). Following his undergraduate career (1867–71), six further years of study was rewarded with a coveted fellowship. In 1881 FitzGerald became Erasmus Smith professor of Natural and Experimental Philosophy, a post which he retained until his death three decades later.[6]

During the arduous preparations for the Trinity fellowship examinations, FitzGerald began to focus his attention on the physical optics of MacCullagh. In 1839 MacCullagh had employed a form of optical ether possessing rotational elasticity to account for the standard phenomena of reflection, refraction and polarization. In contrast, Green, Stokes and other Cambridge mathematicians promoted an elastic solid ether while criticizing MacCullagh's ether for its physical implausibility.[7]

Working outside Cambridge orthodoxy, FitzGerald published in 1879 a paper (refereed by Maxwell at the very end of his life) which both revived MacCullagh's theory and, using his countryman's techniques, extended Maxwell's theory of electromagnetism to reflection and refraction of light. FitzGerald linked Maxwell's expressions for the kinetic and potential energy of the ether to equivalent terms in MacCullagh's theory. Subject to the least action principle, these energy expressions accounted for the complete behaviour of a dynamical system. Despite formidable difficulties with this attempt to reconcile MacCullagh and Maxwell, FitzGerald was convinced of the need to break with the elastic solid orthodoxy which had long kept MacCullagh's theory on the margins of respectability and which now threatened the very survival of Maxwell's electromagnetic theory. Strengthened by FitzGerald's friendship with Lodge and later with Heaviside, that conviction shaped the development during the 1880s of a new and credible body of 'Maxwellian' doctrine.[8]

Lodge spent his early years in his father's business selling clay to Staffordshire potters. Inspired by Tyndall's lectures at the Royal Institution, Lodge took advantage of the diverse opportunities offered in Victorian London for a scientific education. The ambitious Oliver thus began a career in physics in the early 1870s as assistant to G.C. Foster, professor of physics at University College and translator of many German papers on physics for the *Phil. Mag*. During the same period, Lodge became acquainted with, and published two papers on, Maxwell's electromagnetic theory. By 1881 he had been appointed to the new chair of physics at Liverpool University. Like FitzGerald, whom he first met at the Dublin meeting of the BAAS (1878), he possessed from the outset a fanatical commitment to mechanical model-building but his skills at popular exposition and experimentation, combined with a lack of mathematical training, complemented rather than duplicated those of the Dubliner.[9]

Particularly through his textbook, *Modern Views of Electricity* (1889), Lodge played a vital role in promoting the new 'Maxwellian' perspectives on electromagnetic theory at pedagogical and popular levels. Serialized in *Nature*, *Modern Views* went through three editions in Britain and the United States (1889, 1892 and 1907) as well as translations into Russian (1889), French (1891) and German (1896). Its popular success brought criticism as well as acclaim. The French physicist and philosopher of science Pierre Duhem (1861–1916) complained of what he saw as its tendency, through its prolific use of mechanical models, to degrade physics to the level of industry: 'We thought we were entering the tranquil and neatly ordered abode of reason, but we find ourselves in a factory'.[10]

During the decade prior to *Modern Views*, Lodge had become adept at promoting physics in general and energy physics and field theory in particular. In October 1879 he published 'An Attempt at a Systematic Classification of the Various Forms of Energy' in the *Phil. Mag*. (Figure 14.1). His accompanying letter to the editors (including Sir William Thomson) explained that while he had been 'writing a little elementary manual of mechanics lately for [the Edinburgh publishers] Messrs. Chambers his attention had been directed to a certain amount of vagueness and loose language which appears to be current in modern statements concerning energy'.[11]

Presenting his 'Systematic Classification' in twenty simple steps, Lodge rejected as inadequate the more familiar definition of energy as 'the power of doing work'. To illustrate the point he resorted to elementary principles of political economy. A sovereign, for example, had 'an infinite power of buying goods . . . , twenty-shillings worth being bought whenever it is transferred from one man to another'. Lodge explained that the 'proper statement is that a sovereign usually *confers upon the man that possesses it* a certain buying power, which power he loses when he has transferred it; and in this sense money is a power of buying goods'. Hence energy 'is power of doing work in precisely the same sense as capital is the power of buying goods'.[12]

But just as money does not necessarily confer upon its owner any buying power 'because there may not be any accessible person to buy from; and if there be, he may have nothing to sell', so energy usually, but not necessarily, 'confers upon the body possessing it a certain power of doing work, which power it loses when it has transferred it'. He therefore set out a pedagogical analogy:

> Energy corresponds to capital.
> Doing work [upon a body] corresponds to buying.
> Doing antiwork [i.e. work done by a body] corresponds to selling.

The transfer of capital is accompanied by two equal opposite acts, buying and selling; and it is impossible for one to go on without the other. Hence the algebraic sum of all the buying in the world is always zero: this is the law of conservation of capital.

Lodge thus claimed that the 'power of doing work conferred upon a body by the possession of energy does not depend upon the absolute quantity of that energy only, but on its transferability'. He then he distinguished between 'a high or available form of energy' (capable of being 'guided, and all, or nearly all, transferred to any body at pleasure' and hence of doing 'useful' work) from 'a low or unavailable form of energy . . . nearly incapable of being guided, and which transfers itself in directions not required', yielding 'useless' work.[13]

Following the teachings of the masters of 'the science of energy' (especially Maxwell), Lodge emphasized that the 'distinction between high and low forms of energy is a relative one, and depends on our present power of dealing with matter'. Masses of matter 'comparable to our own bodies in size can be handled and dealt with singly; and so they can in general be caused to do work upon, and therefore transfer their energy at pleasure to, any of the numerous accessible bodies which are competent to receive it'. But planets, which could also be treated singly, offered little opportunity for the transfer of energy (apart from tidal energy 'now available to us' for useful work). For the most part, then, 'the kinetic energy of the earth is of no more use to us than a bank-note to Robinson Crusoe'.[14]

Relatively unavailable too was the energy of moving molecules 'because we can only deal with them statistically and not individually'. In a witty footnote Lodge again resorted to the language of elementary political economy for pedagogical purposes:

> An analogy may be drawn between the molecular energy of a body and the money of a bank; of which a reserve fund is kept for internal transfer and transactions between customers, while the excess gets invested in external concerns which have a deficiency, and so becomes available for doing useful work. To make the analogy more complete, the clerks should be uniformly dishonest, or the coffers insecure, so that stored money should dribble away.[15]

Within this framework of energy transfer Lodge began to consider in the same year (1879) the possible production of electromagnetic waves, something which Maxwell himself apparently did not contemplate. FitzGerald, indeed, initially read Maxwell's claim for the mathematical identity of his results with the German action-at-a-distance theories (which took no account of a non-conductor) as an argument against the possibility of energy being transferred in the form of electromagnetic waves from an electrical system (such as a closed system of perfect conductors) into non-conducting space. Instead, FitzGerald took the view, similar to that of Maxwell himself, that light was not produced electrically, but probably as the result of an atomic interaction between matter and aether. FitzGerald's scepticism, made public before the Swansea meeting of the British Association (1880),

BODIES.	ENERGY OF MOTION, OR KINETIC ENERGY.		ENERGY ALTERNATELY KINETIC AND POTENTIAL.	ENERGY OF STRESS, OR POTENTIAL ENERGY.
	Rotation.	*Translation.*	*Vibration.*	*Strain &c.*
Planetary masses	1. *E. g.* Earth's diurnal motion.	2. *E. g.* Earth's annual motion.	3. *E. g.* The moon's libration. Tides. Pendulums.	4. Energy of gravitation. *E. g.* A bead of water. A raised weight.
Ordinary masses	5. *E. g.* Fly-wheel.	6. *E. g.* Cannon-ball. Rivers.	7. Sound-vibrations. *E. g.* Tuning-fork.	8. Energy of strained elastic bodies. *E. g.* Watch-springs.
Particles or molecules ...	9. Part of the heat-energy of fluids.	10. Most of the heat-energy of gases.	11. Heat-energy of solids.	12. Energy of molecular stresses. *E. g.* "Internal work."
Atoms	13. Unknown motions which take place during the act of chemical combination and during dissociation.	14. The translation of atoms is observed in electrolysis.	15. The period of atomic vibration is observed by the spectroscope.	16. Energy of chemical affinity.
Something	17. Magnetism.	18. Electric currents.	19. (1) Discharge of accumulators. (2) Radiation.	20. (1) Electrostatic stress. (2) Electromagnetic stress.

Figure 14.1 Lodge's classification of energy in relation to different classes of bodies. He divided energy into three classes (kinetic, potential and alternatively kinetic and potential) and bodies into five classes (from planets down to aether) (Lodge 1879: 282).

though not published in the *Report*, almost certainly served to direct Lodge's attention away from the subject until 1888, the year in which Heinrich Hertz (1857–94) announced the detection of electromagnetic waves.[16]

By 1882, however, FitzGerald had effectively reversed his stance against the production of electromagnetic waves. His reading of a key passage in Lord Rayleigh's *Theory of Sound* (1877) led him to the conclusion that for an oscillating current 'all the energy is gradually transferred to the medium', contrary to action-at-a-distance theories. As he wrote to the physicist Henry Rowland at Johns Hopkins University in Baltimore in 1882:

> it is most likely that all periodic electric and magnetic [oscillations] are accompanied by a loss of energy just like, and in fact the same thing as, the radiation of heat. In fact it extends the dissipation of energy by radiation to the case of periodically working electric and electro-magnetic machines.[17]

At the Southport meeting of the BAAS (1883) FitzGerald read two brief papers: 'On the Energy Lost by Radiation from Alternating Currents' and 'On a Method of Producing Electromagnetic Disturbances of Comparatively Short Wave-lengths'. Electromagnetic waves of 10 metres wavelength or less, he announced, would be possible. Yet although FitzGerald had already worked out the equations for such energy radiation, electromagnetic waves remained experimentally undetected for five more years.[18]

The third leading member of the 'Maxwellian' group, Heaviside, excelled the others in eccentricity and remained throughout his life on the fringes of English scientific society. Heaviside grew up in comparative poverty and ill-health in the seedier parts of London's Camden Town. His early scientific education seems to have been largely of his own making. But thanks to the influential Charles Wheatstone (1802–75), an uncle by marriage, the young Heaviside began in 1867 a practical career in electric telegraphy.[19]

Following publication of 'On the Best Arrangement of Wheatstone's Bridge for Measuring a Given Resistance with a Given Galvanometer and Battery' in the *Phil. Mag.* (1873), Heaviside's mathematical skill (the more noteworthy because he lacked a Cambridge mathematical education) attracted the attention of Sir William Thomson. Backed by Thomson and Sir William Siemens, Heaviside was admitted in 1874 to the new Society of Telegraph Engineers in the face of opposition from Post Office engineers and officials who apparently regarded him as a mere telegraph clerk. Illness in the same year prompted him to abandon practical telegraphy in favour of private, almost reclusive, electrical research.[20]

From the mid-1850s Thomson had been offering a mathematical analysis (based on Fourier's methods for treating problems of heat flow) of the distortion and retardation of signals which occurred in undersea telegraphy at a time when the first long-distance cables (notably the trans-Atlantic) were being planned. Experiencing such retardation effects for himself on the Anglo-Danish cable at Newcastle in the early 1870s, Heaviside extended Thomson's theory to take into account the phenomenon of self-induction (first described by Faraday and manifested as a tendency of electric currents to oppose any changes in their strength, rather as a machine flywheel). These concerns focused Heaviside's attention less on the electric conductors themselves and more on the space around them.[21]

Maxwell's *Treatise* had offered its early readers a somewhat ambivalent perspective. On the one hand, the energy of the current in a wire and the electrostatic energy could be expressed in terms of vector and scalar potentials. If these potentials were read as fundamental, the *Treatise* could be construed as retaining an action-at-a-distance approach which located the energy of a steady current *within* the wire. On the other hand, the energy of the current could also be expressed in terms of magnetic force and the electrostatic energy in terms of electric force, both expressions placing emphasis on the surrounding medium (ch.11). Five years after Maxwell's death, J.H. Poynting (1852–1914) published an extended treatment in terms of the energy of the electromagnetic field, marking a decisive shift away from potentials to a location of the energy in the field.[22]

Poynting's 'On the Transfer of Energy in the Electromagnetic Field' appeared in the *Phil. Trans.*(1884). Poynting had left Owens College in Manchester for Cambridge in 1872 where he graduated third wrangler four years later. For a brief period before Maxwell's death Poynting worked at the Cavendish Laboratory under the direction of the professor. From 1880 he served as physics professor at Birmingham's new Mason College of Science. His thoroughgoing study of Maxwell's theory inspired the Royal Society paper that Lodge publicly described in 1885 as 'a most admirable and important paper . . . which cannot but exert a distinct influence on all future writings treating of electric currents'.[23]

The fundamental feature of Poynting's investigation was the notion of continuity in the existence of energy. His consequent search for energy in the intervening space and his study of the paths by which it travelled led him to a new theorem about the electromagnetic field: the rate at which energy entered a region of space, where it was stored in the field or dissipated as heat, depended only on the values of the electric and magnetic forces at its boundaries.[24]

A simple but striking application of his 'flux theorem' produced the result that electromagnetic energy did not flow inside a current-carrying wire but flowed through the surrounding space (dielectric) to enter the wire through its sides. Similarly, an application of the theorem to the discharge of a condenser showed that the electromagnetic energy flowed out from between the condenser plates and radially into the current-carrying wire. Poynting summed up his reading of Maxwell's theory as one in which 'currents consist essentially in a certain distribution of energy in and around a conductor, accompanied by the transformation and consequent movement of energy through the field'.[25] The field was now the location of electromagnetic energy.

Lodge's enthusiastic endorsement of Poynting's paper was based on what he saw as 'this new form of the doctrine of the conservation of energy' which was 'really much simpler and more satisfactory than in its old form'. He then claimed that the new version could be demonstrated from two premisses: Newton's 'law of motion' and the denial of action-at-a-distance. With respect to Newton's laws, he believed them to be 'really three very important aspects of one law' which could be expressed in a number of ways including the equality of action and reaction. His preferred expression was that 'Force is always one component of a stress'. Denial of action-at-a-distance required simply the premiss: 'If a stress exist between two bodies they must be in contact'.[26]

Lodge then argued that conservation of energy followed from these two basic premisses:

> not only conservation, but conservation in the new form, viz. the *identification* of energy; thus: If [body] A does work on [body] B it exerts force on it through a certain distance; but (Newton's law) B exerts an equal opposite force, and (being in contact) through exactly the same distance; hence B does an equal opposite amount of work, or gains the energy which A loses. The stress between A and B is the means of transferring energy from A to B, directly motion takes place in the sense AB. And the energy cannot *jump* from A to B, it is transferred across their point of contact, and by hypothesis their 'contact' is absolute: there is no intervening gap, microscopic, molecular, or otherwise. The energy may be watched at every instant. Its existence is continuous: it possesses identity.[27]

Taking seriously the possible objection that two pieces of matter (for example, two molecules A and M) were never in contact, Lodge countered that the 'energy may be transferred from A to M, but not directly'. Thus 'A can act on B, transferring its energy to B, B can act on C . . . handing on the energy to L, which is in contact with, and can act on, M, doing work on it and giving up to it the energy lost by A'. Although he took care to avoid a commitment to the specific nature of the intervening steps, he concluded that 'of course one supposes them to be successive portions of the perfectly continuous space-filling medium Aether'.[28]

As part of his overall goal of constructing and promoting a *reformed* language, Lodge then subjected 'potential energy' to a severe critique. He claimed that the 'usual ideas and language current about potential energy are proper to notions of action at a distance'. While it 'was easy enough to take account of it in the formulae, . . . it was not easy or possible always to form a clear and consistent mental image of what was physically meant by it'. For example, a raised weight such as a stone gained potential energy: but how could 'an inert and quiet stone' be said to possess energy? To reply that '"the system of earth and stone possesses energy in virtue of its configuration"' was true, but also 'foggy'. Admitting universal contact action dispelled the fog: 'the energy is seen to be possessed, not by stone or earth or by both of them, but by the medium which surrounds and presses them together'.[29]

At the same time, however, Lodge confessed that he did not intend to claim that 'the natures of gravitation, elasticity, cohesion, &c. become clear'. To account for the stress in the medium was 'a much higher and more difficult problem'. He only wanted his readers to recognize the '*seat* of the energy' in the surrounding medium.[30] Yet the demand for an explanation, or at least illustration, of how the medium might operate brought forth from Lodge and his contemporaries that immense proliferation of mechanical models for which Duhem was to indict most Victorian physicists.

This new emphasis on energy transfer in physical theory in general and electromagnetic theory in particular helps explain why the British liking for mechanical models reached such a peak in the 1880s. Philosophers of science have often cited Sir William Thomson's remark in his 'Baltimore Lectures' (1884) concerning electromagnetism and the wave theory of light: 'I never satisfy myself until I can make a mechanical model of a thing. If I can make a mechanical model I can understand it. As long as I cannot make a mechanical model all the way through I cannot understand; and that is why I cannot get the electro-magnetic theory'.[31] If Thomson appeared in retrospect as the most uncompromising exponent of mechanical models in Victorian physical science, his was by no means a lone voice. Just as his contemporaries (especially Rankine and Maxwell) had once placed great emphasis on mechanical hypotheses, so too did members of the younger generation of British physicists.

Mechanical models served a variety of functions: illustrative and pedagogical; directing enquiry among otherwise recondite phenomena; demonstrating the possibility that those phenomena could in principle admit of some kind of mechanical explanation; and even offering the prospect that the model itself reflected more or less accurately the 'true mechanism' of nature. Above all, mechanisms provided an exemplar of continuity in energy transfer: in proper mechanisms there could be no action-at-a-distance.[32]

FitzGerald's ingenious 'wheel and band' model (1884–5) offered one such mechanical model to illustrate the nature of energy transfer involved in Poynting's new theorem. As Fitzgerald told Lodge: 'I have been constructing a model ether . . . as I want it to illustrate Poynting's great discovery that the energy of an electric current must come in at its sides and is not carried along with the current'. Fitzgerald subsequently developed this illustrative model into a wide-ranging mechanical representation in two dimensions of Maxwell's electromagnetic equations.[33]

Not content with illustrative models, FitzGerald simultaneously sought a 'realistic' model of the ether in the form of a 'vortex sponge'. In its conception the vortex sponge model owed much to William Thomson's earlier attempts to construct a vortex theory of matter. Ironically, it was in part to counter Thomson's commitment to an elastic-solid ether in his 'Baltimore Lectures' (1884) that FitzGerald put his faith in a hydrodynamical model which aimed to explain all the phenomena of nature in terms of matter in motion, or in terms of kinetic energy. Thomson too became enthusiastic for a time. But by 1890, weighed down by its many conceptual difficulties, the vortex sponge ether lost much of its appeal.[34]

The spectacular proliferation and conspicuous collapse of such grand speculative theories prompted some British physicists to argue in favour of mathematical laws rather than mechanical hypotheses. This approach had a long pedigree. Thomson and Maxwell, for example, had appeared to oscillate between a commitment to laws ('mathematical theory' in Thomson's phrase) on the one hand and a belief in the ultimate mechanical nature of the physical world while reserving their scepticism for specific mechanical hypotheses. A similar attitude characterized some of the later 'Maxwellians'. In the early 1890s Poynting criticized Lodge's seeming belief in the truth of his mechanical models. Emphasizing instead the illustrative role of mechanical models and the formulation of electromagnetic laws, he urged physicists to 'leave the ether out of account'.[35]

With rather less scepticism towards mechanical explanation, Heaviside too had far less enthusiasm for mechanical models than his friends Lodge and FitzGerald. From 1883 he began publishing in the *Electrician* a series of articles on 'The Energy of the Electric Current'. At first he followed the conventional perspective of regarding the energy of the electric current as analogous to the flow of a fluid in a pipe. A relatively small amount of energy passed from the wire into the surrounding medium, there to be stored by the rotation of 'flywheels' in the ether. Published in mid-1884 (and apparently without knowledge of Poynting's work), Heaviside's 'Transmission of Energy into a Conducting Core' shifted the emphasis away from the flow of energy in the wire to considerations of the flow of energy in the field. Basing the analysis on the conviction that one needed to follow the paths of electromagnetic energy, Heaviside independently arrived at the energy flux theorem six months after Poynting.[36]

Heaviside was not bound by academic orthodoxy. While Cambridge mathematicians used Thomson and Tait's *Treatise* as a textbook resource for Lagrangian and Hamiltonian dynamics, Heaviside seized upon the 'principle of activity' (ch.10) which expressed Newton's third law in terms of force times velocity or rate of working (action) equivalent to rate of increase of kinetic energy (reaction). Realizing that the 'principle of activity' could not be formed directly from Maxwell's equations (by finding the rate at which the electric and magnetic forces act on the 'velocities' or currents), Heaviside set about reworking Maxwell's 'General Equations of the Electromagnetic Field'. Vector and scalar potentials permeated Maxwell's original list of thirteen principal equations. As Bruce Hunt has shown, from eight of these equations Heaviside obtained three equations which contained no potentials. He finally constructed a fourth equation expressing Faraday's law of electromagnetic induction relating rate of change of magnetic force to electric force, again without potentials. Rate of working and energy flow could then be derived directly from these four concise and symmetrical equations.[37]

First published in the *Electrician* early in 1885, these four equations became known as 'Maxwell's Equations'. Heaviside's formulation had eliminated all remnants of action-at-a-distance embodied in the potentials employed by Maxwell. The theoretical issue of the electric potential in particular was debated publicly (though characteristically in the absence of the retiring Heaviside) at the Bath meeting of the BAAS (1888) when general agreement was reached as to the desirability of Heaviside's elimination of potentials. The full emphasis was now on the energy of the field.[38]

In the summer of 1888 came news from Germany of Hertz's experimental generation and detection of electromagnetic waves in free space. Working with Helmholtz in Berlin for several years, Hertz was well acquainted with his master's generalized electrodynamics which rendered the rival theories of Weber, Neumann and Maxwell special cases of his own. While in Britain action-at-a-distance theories had long since received short shrift, in Germany it was Maxwell's field theory which looked out of place among action-at-a-distance orthodoxy. All the theories tended to account equally well for standard experimental results, but Maxwell's theory differed in its prediction of electromagnetic effects from dielectric displacement currents. As early as 1879 Helmholtz had urged Hertz to try to detect such effects. Given formidable experimental difficulties, it was not until late 1887 that he succeeeded to his own satisfaction. Recognizing that the key feature of field theory lay in electromagnetic action in space (rather than material dielectrics), Hertz quickly moved to produce and detect electromagnetic waves in free space, that is in a vacuum.[39]

The initial credibility conferred upon Hertz's experimental work was largely contingent upon the forum of the BAAS at Bath. A formidable array of men of science with electrical expertise assembled in the ancient spa town: Sir William Thomson, Lord Rayleigh, FitzGerald, Rowland and Lodge. As president of Section A it was FitzGerald who made the formal announcement. Predictably, FitzGerald, with his deep commitment to Maxwellian field theory, chose to represent Hertz's achievement as confirmation of that field theory against action-at-a-distance: 'Henceforth I hope no learner will fail to be impressed with the theory – hypothesis no longer – that electromagnetic actions are due to a medium pervading all space, and that it is the same medium by which light is propagated; that non-conductors can, and probably always do, as Professor Poynting has taught us, transmit electromagnetic energy'.[40]

Whereas in Germany Hertz's discovery might initially have gone unnoticed, the BAAS meeting provided Hertz with rapid publicity. From the leading authorities in mathematical physics to the principal newspapers came enthusiastic responses. In the next few years translations of Hertz's papers appeared in the most widely read scientific journals (*Phil. Mag.* and *Nature*), culminating in a collection of Hertz's papers (1892) with a preface by no less an authority than Sir William Thomson.[41]

Although in the few remaining years of his short life Hertz interacted closely with the British 'Maxwellians', the German physicist differed markedly in his interpretation of Maxwellian doctrine. Defining Maxwell's theory as 'Maxwell's system of equations' in his *Electric Waves* (1892), Hertz appeared to separate the mathematical content of Maxwell's theory from its physical foundations of the electromagnetic field. In large part Hertz's move reflected his desire to avoid the deep conflict over physical theory which divided Continental traditions (now exemplified by Helmholtz's electrodynamics) from the British conceptions (embodied above all in Heaviside's Maxwellian exposition).[42]

The British 'Maxwellians' of course would have none of this 'nihilism'. A review of Hertz's *Electric Waves* for *Nature* (1893), probably by FitzGerald, noted that Hertz 'seems content to look upon Maxwell's theory as the series of Maxwell's equations'. But, he remonstrated, 'Any exposition of Maxwell's theory which does not clearly put before the reader that energy is stored in the ether by stresses working on strains, is a very incomplete representation of Maxwell's theory'. Crucial to the 'purified' Maxwellian doctrine of FitzGerald, Lodge and Heaviside, then, was the physical conception of energy flux in a dynamical ether.[43]

From the point of view of the 'Maxwellians', just as corrupt an interpretation of the sacred *Treatise* lay with the Cambridge mathematicians. The post-Maxwell generation of J.J. Thomson and Larmor, among others, were guilty of following the Lagrangian letter and not the aetherial spirit of the *Treatise*. Beginning in the 1890s and culminating in his *Aether and Matter* (1900), Joseph Larmor made the principle of least action central to his electrodynamics. For Heaviside, least action was 'a golden or brazen idol' for Cambridge men to worship. For FitzGerald, it produced an 'analytical juggle'. But for Larmor least action 'comprehends in itself the whole of mechanical science'.[44]

Larmor's strategy was to treat of the molecular level which had been to a large extent by-passed in Maxwell's *Treatise* and by its Maxwellian interpreters. In particular, Maxwell and the Maxwellians had not engaged with the question of how electrical conduction occurred. Larmor, aided by a lengthy correspondence with FitzGerald, slowly came to the view that currents could be construed as the movement and interaction of microscopic particles or 'electrons'. These particles in the electromagnetic ether provided the basis for Larmor's '*electronic theory*' of matter and for the grand dynamical programme set forth in *Aether and Matter*. The mechanical had been replaced by the electromagnetic philosophy of nature.[45]

The major realignments of dynamical theory undertaken by Larmor in his bid to provide a molecular synthesis had, in his view, an important consequence for conceptions of energy:

> One effect of admitting a molecular synthesis of dynamical principles such as the one here described is to depose the conception of energy from the fundamental or absolute status that is sometimes assigned to it; if a molecular constitution of matter is fundamental, energy cannot also be so. It has appeared that we can know nothing about the aggregate or total energy of the molecules of a material system, except that its numerical value is diminished in a definite manner when the system does mechanical work or loses heat. The definite amount of energy that plays so prominent a part in mechanical and physical theory is really the mechanically available energy, which is separated out from the aggregate energy by a mathematical process of averaging, in the course of the transition from the definite molecular system to the material system considered as aggregated matter in bulk.[46]

Larmor here claimed that this energy, though 'definite', was not conserved in unchanging amount. Energy did not therefore share equal status with matter: energy 'merely possesses the statistical, yet practically exact, property, based on the partly uncoordinated character of molecular aggregation, that it cannot spontaneously increase, while it may and usually does diminish, in the course of gradual physical changes'.

Energy physics and physical chemistry: the science of energetics

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, different perspectives, emphasizing the independence of energy from mechanics, began to be promoted among German-speaking scientific communities as part of a widespread reaction against capitalistic materialism during the 'Great Depression' (c.1873–96). The more radical versions, especially the 'Energetics' of Ostwald, originated outside mainstream German mathematical physics and soon attracted much critical attention from a younger generation of German physicists.[47]

From the 1880s Ernst Mach (1838–1916) condemned the widespread assumption that mechanics comprised the basis of all physical phenomena and argued instead for a 'phenomenological' view in which sensory perceptions would constitute the real object of physical research. He held up the principle of conservation of energy as an ideal: although mechanical theories had aided in 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. Mach located the starting point of his own mature epistemology in the first edition of his *History and Root of the Conservation of Work* (1872):

> In this pamphlet . . . I made the first attempt to give an adequate exposition of my epistemological standpoint – which is based on a study of the physiology of the senses – with respect to science as a whole, and to express it more clearly in so far as it concerns physics. In it both every *metaphysical* and every one-sided *mechanical* view of physics were kept away, and an arrangement, according to the principle of economy of thought, of facts – of what is ascertained by the senses – was recommended.[48]

First published in 1883, Mach's *Development of Mechanics* (*The Science of Mechanics* in its English translation) went through five German and three American editions over the next quarter century. In that and other works during the same period Mach set forth his view that the interdependence of phenomena, rather than their reduction to 'metaphysical' and 'mechanical' conceptions such as atoms and molecules, was to be the goal of natural science. Mechanics had its place in science, but it was no longer fundamental: any 'view that makes mechanics the basis of the remaining branches of physics, and explains all physical phenomena by mechanical ideas, is in our judgment a prejudice'.[49]

Although not to be identified as an 'Energeticist' himself, the severity of Mach's critique of mechanical foundations (especially atomism) added considerable authority to the new doctrines of what became known as the 'Energeticist School'. Following publication of a treatise on the energy principle, *Die Lehre von der Energie* (1887), and appointment as extraordinary (that is, junior) professor of physics at the Dresden technical institute, Georg Helm in 1890 attempted to derive the equations of motion from the conservation of energy and thereby to assimilate mechanics to energetics. In the same year, Helm forged an alliance with the ambitious physical chemist, Wilhelm Ostwald.[50]

The principle of the equivalence of heat and work, together with the associated mechanical theory of heat, had long offered the possibility of a new mechanical theory of chemistry. In his *Erhaltung der Kraft* (1847) Helmholtz had shown that 'Hess's Law', that 'no matter by which way a compound may come to be formed, the quantity of heat developed through its formation is always constant', was a direct consequence of the conservation principle. Hess's work (1839–42) had been concerned to show that heats of dilution offered a reliable measure of the problematic notion of chemical affinity. Thus while chemical affinity might or might not be due to microscopic forces of attraction and repulsion (in accordance with Laplacian doctrine), its effects could now be measured unambiguously in terms of the heat developed in chemical processes.[51]

Although Joule and others in Britain had engaged with similar questions of chemical affinity and its measurement in terms of thermal and mechanical effects, the construction of a science of 'thermochemistry' was due largely to the efforts of the Danish chemist Julius Thomsen (1826–1909) and his French rival Marcellin Bertholet (1827–1907). A friend and colleague of L.A. Colding whose measurements of the equivalence of heat and work had been at first little known outside Denmark, Thomsen set out his basic thermochemical principles in 1854. Affinity was to be understood as the 'force which unites the component parts of a chemical compound'. To overcome the affinities and thus to split up a compound required a force whose quantity 'can be measured in absolute terms; it is equal to the amount of heat evolved by the formation of the compound' from its constituents.[52]

In general Thomsen claimed that 'Every simple or complex action of a purely chemical nature is accompanied by evolution of heat'. Actions which appeared to involve an absorption of heat could not be purely chemical in nature. As professor of chemistry at the University of Copenhagen from 1866, Thomsen's thermochemical research culminated in the German-language *Thermochemische Untersuchungen* (1882–4). The programme included the extension of thermochemical principles to structural (especially organic) chemistry.[53]

Equally ambitious was Berthelot's thermochemistry which originated in the mid-1860s from his extensive research in organic chemistry and which drew on previous experimental measurements of heat in chemical reactions. Berthelot's 'principle of molecular work' (*le travail moléculaire*) dating from 1865 stated an equivalence between internal work and heat changes in chemical reactions. In the same year he introduced the terms 'exothermic' and 'endothermic' for chemical reactions which involved the evolution and absorption of heat respectively.[54]

Berthelot's 'principle of maximum work' (1864–73) stated that 'Every chemical change accomplished without the intervention of external energy [*d'une énergie étrangère*] tends to the production of that body, or system of bodies, which disengages most heat'. This principle performed a parallel causal function to that of least action in physics: the tendency of a system of bodies towards a future state governed the behaviour of the system. The principle offered a rationale for spontaneous chemical reactions which, in Berthelot's view, necessarily occur if accompanied by an evolution of heat: 'Every chemical change which can be accomplished without the aid of a preliminary action, and without the intervention of external energy . . . necessarily happens if it disengages heat'. This principle, embodied in Berthelot's two-volume treatises *Essai de mécanique chimique fondée sur la thermochimie* (1879–81) and *Thermochimie. Données et lois numériques* (1897), formed the core of Berthelot's thermochemistry, the centrepiece of French physical chemistry in the late nineteenth century.[55]

The patronage, power and prestige wielded by Berthelot in France, however, was not matched by his influence abroad. Heavily criticised on every front by Thomsen in the period 1872–86, the principles of thermochemistry as a whole came under sporadic attack from a variety of sources including Lord Rayleigh who addressed the Royal Institution in a lecture (published in *Nature*) 'On the Dissipation of Energy' (1875). Rayleigh highlighted the need for chemists to take into account the principle of dissipation of energy, a principle absent from Thomsen's and Berthelot's thermochemistry.[56]

'The chemical bearings of the theory of dissipation are very important', Rayleigh told his audience, 'but have not hitherto received much attention'. Chemical transformations which violated the theory of dissipation were impossible. On the other hand, transformations involving dissipation did not necessarily occur spontaneously: 'Otherwise, the existence of explosives like gunpowder would be impossible'. Rayleigh then examined critically and rejected the thermochemical assumption that 'the development of heat is the criterion of the possibility of a proposed transformation'.[57]

Rayleigh's 1875 lecture, widely known through its appearance in *Nature*, coincided with the publication in the United States of the early thermodynamic papers of Gibbs (ch.12). While sympathetic to the extent of seeking support for a Royal Society award for Gibbs in the early 1890s, Rayleigh told the American physicist in 1892 that his thermodynamic paper 'On the Equilibrium of Heterogeneous Substances' had been 'too condensed and too difficult for most, I might say all, readers'. Rayleigh's remarks reflected much stronger views expressed privately to him by Lord Kelvin on two occasions. 'I feel very doubtful as to the merits of Willard Gibbs' applications of the "Second law of Thermodynamics"', he wrote in September 1891. 'I find *No* light or leading [sic] for either chemistry or thermodynamics in Willard Gibbs', he asserted five months later.[58]

In contrast Ostwald translated Gibbs's memoirs into German in 1892. The chemist and his disciples constructed and promoted the new science of physical chemistry largely on the basis of Gibbs's thermodynamic approach. That approach provided physical chemists with some of their most fundamental tools, including the 'phase rule' and 'chemical potential'. And Helm soon annexed Gibbs and his writings to the cause of 'Energetics', though Gibbs himself never identified with the doctrines of that school. In the French provinces, outside the kingdom of Berthelot, the young Duhem also became enamoured of Gibbs's thermodynamics in his crusade against his countryman's thermochemistry. Others, such as Hermann Helmholtz and Max Planck, began their studies in chemical thermodynamics apparently unaware of Gibbs's papers.[59]

Unlike Gibbs, nothing hindered the promotion of Helmholtz's 1882 memoir '*Die Thermodynamik chemischer Vorgänge*' ('Thermodynamics of Chemical Processes'). Against the thermochemistry of Thomsen and Berthelot, Helmholtz distinguished between the 'bound' energy (obtainable only as heat) and 'free' energy (available for useful work and conversion to other forms) of chemical reactions. The free energy was then equal to the total energy less the bound energy (expressed, as with Clausius, in terms of the product of absolute temperature and entropy change). The free energy, rather than the heat of reaction, then became the driving agent for chemical and physical processes, determining the direction of the reaction. Consequently, in all spontaneous reactions at constant volume and temperature the free energy must decrease. Similarly, only at absolute zero would Berthelot's principle of maximum work hold good. Furthermore, the new equation (subsequently known as the 'Gibbs–Helmholtz Equation') showed how at ordinary temperatures most reactions would be exothermic, but, particularly at high temperatures, some reactions could be endothermic.[60]

By the time that Thomsen and Bertholot shared in the award of the Royal Society's Davy Medal (1883), the science of thermochemistry was becoming unfashionable among the *avant garde* of chemical science. Ostwald rapidly became a powerful and persuasive leader of that new generation. Born in Riga to German parents, he remained in Latvia for more than three decades. Graduating from the University of Dorpat in 1875, he began lecturing on the subject of chemical affinity in his capacity as *Privatdozent* in 1876. By 1881 he had been appointed professor of chemistry at the Riga Polytechnic Institute. Written during his tenure at the Polytechnic, Ostwald's textbook on general chemistry, *Lehrbuch der allgemeinen Chemie* (1885–7), soon became central to his campaign of promoting the establishment of physical chemistry as a new scientific discipline.[61]

During this period, and in collaboration with the Swedish chemist S.A. Arrhenius (1859–1927), Ostwald adopted a theory of electrolytic dissociation according to which the molecules of chemical compounds dissociated into electrically charged ions when in solution. This theoretical perspective transformed Ostwald's earlier work on chemical affinities and provided a comprehensive and unified account of many physico-chemical phenomena such as the behaviour of weak acids and bases and the properties of solutions. It also shaped a whole experimental programme of quantitative physical chemistry.[62]

In 1887 Ostwald accepted the chair of physical chemistry (the only such German chair) at the University of Leipzig, a post which he retained until early retirement to his private estate and country house aptly known as *Landhaus Energie* around 1905–6. Ostwald's Leipzig years coincided with his vigorous promotion both of the discipline of physical chemistry and of a broader programme of Energetics. With Nernst as his principal assistant, the laboratory programme (linked to the theory of electrolytic dissociation) attracted many young chemists from overseas, especially from the United States.[63]

Central to his programme of physical chemistry were transformations of energy and the doctrines of chemical thermodynamics initiated in the late 1870s and early 1880s by Gibbs and Helmholtz. Beginning at Leipzig with his

inaugural lecture on 'Energy and its Transformations', Ostwald promoted his Energeticist approach in a series of lectures and publications. In 1891–92, for example, Ostwald presented his 'Studies on Energetics' to Leipzig's leading scientific society. Arguing that the advance of thermodynamics contrasted with the sterility of attempts to reduce physics and chemistry to mechanics through molecular-mechanical approaches such as the kinetic theory, he emphasized the problems of providing a satisfactory mechanical interpretation of temperature. He therefore proposed substituting energy for mass in the absolute system of measurement. More radical still was his view that mass, no longer a fundamental entity, should be subsumed under energy, now postulated as the primary 'substance' in nature.[64]

The Energeticist school had formidable critics, not least in Germany itself. At the annual meeting of the German Society of Scientists and Physicians held in Lübeck (1895), Boltzmann launched a fierce attack on the presentations of Helm ('On the Present State of Energetics') and Ostwald ('The Conquest of Scientific Materialism'). As one Boltzmann partisan observed, the attack resembled 'the fight of the bull [Boltzmann] with the lithe swordsman [Ostwald]. But this time, in spite of his swordsmanship, the toreador was defeated by the bull'.[65] In a follow-up critique published in the *Annalen der Physik*, Boltzmann condemned Ostwald's Energetics not only for perceived mathematical and physical errors but also for its false promise of easy rewards. Boltzmann, however, was not prepared to defend an approach based on mechanical-molecular hypotheses:

> Probably no-one holds energy to be a reality any more; or believes that it has been proven without question that all natural phenomena can be explained mechanically . . . We are much more cautious nowadays . . . The precise description of natural phenomena, as independent as possible from all hypotheses, now generally is recognized to be most important . . . For a long time already, even in the theory of gases, one no longer regards molecules exclusively as aggregates of material points, but rather as unknown systems determined by generalized coordinates.[66]

Presenting the Energeticists as the dogmatists, Boltzmann labelled their approach as a mere classification system which required distinct forms of energy and its laws for each different branch of physics rather than offering the unity which a mechanical conception could provide.[67]

Of the new generation of German theoretical physicists attaining academic eminence in the late nineteenth century, Max Planck (1858–1947) had initiated himself into thermodynamic perspectives with a doctoral dissertation at Munich (1880) concerned with a reformulation of entropy. By the late 1880s he had been awarded second prize by the Göttingen Philosophical Faculty for an historical and analytical essay on the conservation of energy. While professor of theoretical physics at Kiel (1885–92) he sought to give the second law of thermodynamics the universal generality accorded to the first law. Planck's approach to thermodynamics had much in common with that of Gibbs and Ostwald in its generality and in its independence from molecular physics. But he became increasingly hostile to the Energeticists on account of what he saw as their failure to differentiate between reversible and irreversible processes in nature.[68]

Ostwald regarded entropy, unlike energy, as a derived concept which he interpreted in terms of the dissipation of energy associated with radiation. By 1893 Planck had based his own interpretation of the second law on the broad empirical postulate that irreversible processes do exist in nature. The second law therefore treated of the direction that a process takes and as such could not be assimilated to the first law. Rejecting both the anti-mechanist interpretation of Ostwald and the mechanistic reductionism of Helmholtz and Clausius, Planck gradually moved closer to Boltzmann's probabilistic interpretation of the second law as he investigated the energy spectrum of black body radiation. With the benefits of retrospective rationalisation, twentieth-century physicists would present Planck's radical introduction of 'energy quanta' into these researches around 1900 as crucial to the shift from 'classical' to 'modern' physics.[69]

The shifting alliances within German theoretical physics left little space for the Energeticist programme. But Ostwald directed his efforts to a much wider stage by offering Energetics as a programme for the world, relevant to all levels of physical and living nature, including human society and civilization itself. In his *Naturphilosophie* (1910), for example, he asserted that the law of energy conservation 'must also be regarded as operative in all the later sciences, that is, in all the activities of organisms, so that all the phenomena of life must also take place within the limits of the law of conservation':

> Thus, the entire mechanism of life can be compared to a water-wheel. The free energy corresponds to the water, which must flow in one direction through the wheel in order to provide it with the necessary amount of work. The chemical elements of the organisms correspond to the wheel, which constantly turns in a circle as it transfers the energy of the falling water to the individual parts of the machine.[70]

Furthermore, civilization or culture, understood as that which 'serves the social progress of mankind', consisted in 'improved methods for seizing and utilizing the raw energies of nature for human purposes'. Conflicts between nations or between social classes acted to destroy 'quantities of free energy which are thus withdrawn from the total of real cultural values'. As Ostwald expressed the point in his *Energetic Imperativ*: 'Waste no energy. Utilize it!'[71]

Epilogue

> At Clerk Maxwell's we did our papers in the dining-room and adjourned for lunch to an upper room, probably the drawing-room, where Clerk Maxwell himself presided. The conversation turned on Darwinian evolution; I can't say how it came about, but I spoke disrespectfully of Noah's flood. Clerk Maxwell was instantly aroused to the highest pitch of anger, reproving me for want of faith in the Bible! I had no idea at the time that he had retained the rigid faith of his childhood, and was, if possible, a firmer believer than Gladstone in the accuracy of Genesis.
>
> *Karl Pearson recounts his old Tripos days at Cambridge during the mid-1870s*[1]

Pearson's recollection of a verbal conflict with the Cavendish professor of experimental physics suggests that Clerk Maxwell was at heart a biblical literalist, committed to the truths of the sacred text imbibed from his earliest years in Scotland. We have seen, however, that Maxwell's theological perspectives were vastly more refined than Pearson's rather condescending remarks imply. Possessing a profound distaste for the perceived anti-Christian materialism of metropolitan naturalists, Maxwell and his fellow North British scientists of energy had not only embedded their new natural philosophy in the cultures of presbyterianism but had also been ready to deploy that natural philosophy in the service of a Christianity suitable to the wants of Victorian Britain.

From Reformation times, Scottish Calvinism had been embodied in the *Westminster Confession of Faith* (1647). That text had opened with the ringing declaration that 'Although the light of nature, and the works of creation and providence do so far manifest the goodness, wisdom, and power of God, as to leave men inexcusable; yet they are not sufficient to give that knowledge of God, and of his will, which is necessary to salvation'. *The Confession of Faith* therefore proclaimed the Holy Scripture as the means by which God revealed Himself 'for the better preserving and propagating of the truth, and for the more sure establishment and comfort of the Church against the corruption of the flesh, and the malice of Satan