5

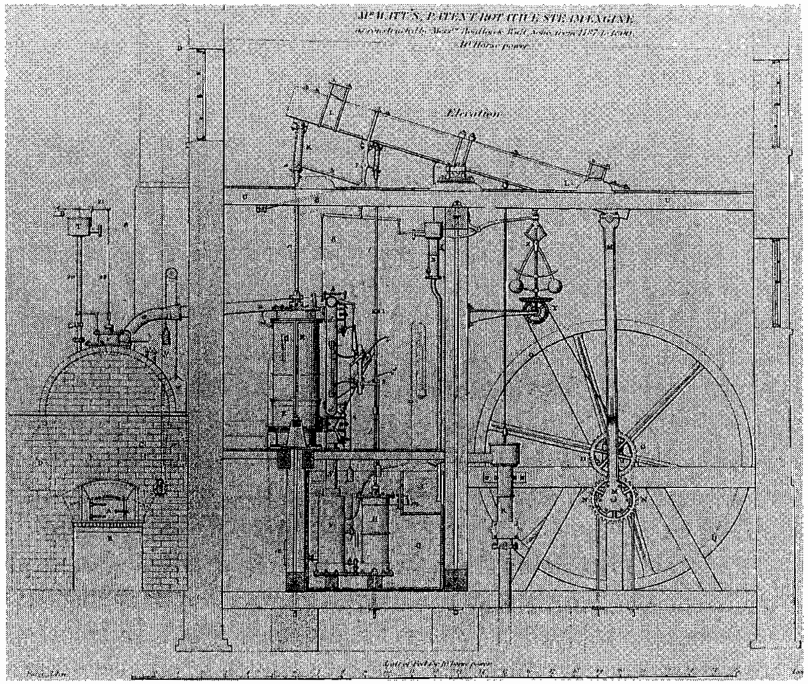
The Science of Work

As the nineteenth century progressed, the concept of work was becoming a focus of attention to an unprecedented degree. More than an occupation, a means of earning a living, or even an indicator of social status, work was increasingly regarded as a moral imperative as much as a physical necessity. Work was treated as a measure of a person's moral worth in just the same way as it was an indicator of an individual's economic value. The key to this in many ways was of course the Industrial Revolution. Massive transformations were taking place in the organization of labour in factories and workplaces. New machines and processes were deskilling workers, introducing new categories of labor, and changing perceptions of what it meant to work. Andrew Ure, the Scottish chemist and enthusiast for the new factory system—"the Pindar of the automatic factory,"[1] as Karl Marx called him—remarked gleefully that the very meaning of the word "manufactory" (later shortened to the now-familiar "factory") had been turned on its head by the progress of industry: "The term Manufacture, in its original signification, undoubtedly means a work performed by hand; whereas at present it almost signifies a work performed *without* hands."[2] The machine seemed to be taking over in the world of work. The new

---

[1] K. Marx, *Capital* (1867; reprint, Harmondsworth: Penguin Books, 1976), 544.

[2] A. Ure, *The Philosophy of Manufactures* (London, 1835), 1.



5.1 James Watt's steam engine. Trying to understand the relationship between heat and motion in engines such as this would play an important role in the development of nineteenth-century thermodynamics.

science of political economy, drawing largely on Adam Smith's hugely influential *Wealth of Nations*, published in 1776, sought to make sense of these transformations and particularly of the new role machinery seemed to be taking on at the center of production. The focus of attention was the steam engine, hailed as an unparalleled new source of productive power.

The hero of steam was the Scotsman James Watt (figure 5.1). He was not, of course, the actual inventor of the steam engine. Inventors such as Thomas Savery and Thomas Newcomen had already applied the power of steam to practical use, using their engines to pump water out of mines. Watt was celebrated, however, for the improvements he had carried out on the steam engine, significantly increasing its efficiency with his invention of the separate condenser. He was the archetypal self-made man to be admired for the way in which he had put his own ingenuity and knowledge to work. Originally a Glasgow instrument maker in the 1760s, he was seen as having put his links to natural philosophers and chemists such as Joseph Black and William Cullen, both experts on the science of heat, to good use. The rapid expansion in use of the steam engine following Watt's innovations drew increasing philosophical interest in its workings. Men of science eager to demonstrate the practical utility of their vocations speculated on its operations. The science of heat increasingly became the focus of intense philosophical concern. Some natural philosophers argued that heat was an imponderable fluid like light or electricity. It was the presence or absence of this fluid—called "caloric"—that made a body hot or cold. Others suggested that heat should be regarded as vibrations in the particles that made up a body. The more motion was imparted to these particles, the hotter the body appeared to be.

The steam engine was widely recognized as having played a major role in bringing about Great Britain's industrial supremacy by the end of the eighteenth century. To Britain's enemies and industrial rivals, conquering the steam engine seemed the key to conquering the nation as well. Revolutionary France, in particular, regarded the systematic application of science to industry as being as much a prerequisite of supremacy as was the valor of its soldiers. One product of the Revolution in France was the systematic training of engineers and men of science. The prestigious École Polytechnique was devoted to producing cadres of trained men able to put their scientific and technical skills at the service of the state. Even following Napoleon's defeat this focus on scientific education continued. Sadi Carnot, the son of a hero of the revolutionary wars and a pioneer of the new science of work, was a direct product of this kind of training. His work combined political economy and scientific acumen to produce a new theory of the working of the steam engine and the best means to increase its efficiency and place it at the service of France.

Efficiency was the goal for a new generation of English and Scottish natural philosophers as well. Men such as James Prescott Joule in Manchester and the Thomson brothers, James and William, in Glasgow came from heavily industrial backgrounds. Their scientific values, like their moral and religious values, were the products of booming commercial cities where a premium was placed on hard work and an eye for making the most from every shilling. In scientific terms that meant finding and defining the conditions under which engines of all kinds worked best—how to maximize their outputs for a minimum outlay in terms of fuel and labor. Natural philosophers from hardheaded industrial backgrounds wanted to know how to minimize waste in nature as well as the factory. The new science of heat—thermodynamics—forged out of British industrial culture during the 1840s and 1850s was not just about understanding the steam engine, which was increasingly regarded as the model for the way in which nature worked. William Thomson, knighted and eventually elevated to the peerage for his services to industry, used Carnot's theories and Joule's experiments to make the science of thermodynamics the exemplar of a whole new way of doing physics. Thermodynamics could demonstrate how the Universe would end in heat death. It could also be used to pour scorn on the claims of geologists and evolutionary theorists concerning the development of life on earth.

New ways of doing physics were emerging in the German lands as well. German natural philosophers of the 1840s were turning their backs on the speculative *Naturphilosophie* of the previous generation. German science as it stood at the end of the eighteenth century and the first few decades of the nineteenth was widely regarded as having become bogged down in metaphysics and rampant, unsupported speculation. A new generation of Young Turks aimed to revitalize German science and make their own careers at the same time, by refounding their disciplines on a secure foundation of empiricism, materialism, and rationalism. New scientific institutions proliferated along with new opportunities to promulgate new visions of nature and the best ways of uncovering its secrets. This was an atmosphere in which ambitious young men of science such as Hermann von Helmholtz and Rudolf Clausius could put forward grand new generalizations founded on a new vogue for careful experimentation. The new generation of German men of physics prided themselves that however grandiose their theories, they were carefully grounded in sober reality. Like their French, English, and Scottish counterparts, they sought to take the steam engine and turn it into a model of the universe.

The dynamical theory of heat as it was developed during the course of the nineteenth century posited a central role to the man of science in the development of Victorian culture. Scientific culture, according to the vision both of nature and society put forward by the pioneers of this new science, was industrial culture as well. The steam engine and its offshoots provided the force that powered Victorian society. According to the confident and hard-nosed natural philosophers who espoused the new physics of work, something very much like it provided the powerhouse on which the cosmos ran as well. The universe operated on the same principles as those that governed, or at the very least ought to govern, the well-regulated Victorian factory. Such a synthesis placed the physicist at the center of the action. He understood the dynamics of nature and of society and could therefore be trusted to oversee their operations. Across Europe and America during the nineteenth century, as men of science sought to forge careers for themselves and a secure cultural niche for the disciplines they were in the process of constructing, this strategy was played out over and over again. Constructing the science of work was part of the process of constructing the Victorian physicist in relation to his culture.

Engineering France

Even before the French Revolution, engineering education was already playing an increasingly important role in the thinking of French state officials, particularly in the military. Following the upheavals of the last two decades of the eighteenth century, major reforms took place within the French educational system, just as they did in French society more generally. These educational reforms were implemented with a view to putting in place a highly centralized regime of education, designed to produce highly technically proficient military officers fit to serve in the modern "grande armée." The centerpiece of this new technical educational system was the École Polytechnique. Potential members of the officer class were trained there in the latest developments in science as an essential element in acquiring the knowledge necessary to engage in modern warfare. Graduates of the école, as well as being trained for the military, were prepared for a wide range of public services. Under the leadership of revolutionary pioneers such as Gaspard Monge, the école was conceived as an institution devoted to the widest possible dissemination of technical knowledge. Knowledge gained there could be put to work in improving the state of French industry, much as it might be employed to build bridges or improve military ballistics.

One figure in particular provides an ideal example of the close links in France during this period between revolutionary politics, the military, and industrial organization. Lazare Carnot—a member of the Committee of Public Safety under that architect of the Terror, Robespierre—was a hero of the Revolution; he later became one of the most prominent of Napoleon's generals. Carnot was deeply engaged in technical matters as well. He was one of the leading figures behind the École Polytechnique. He played a crucial role in efforts to introduce the division of labor and new machinery into French industry during the closing years of the eighteenth century. The aim was quite explicit. Revolutionary France badly needed large quantities of armaments to fight a war on several fronts. At the same time, contemporary commentators were well aware of the military advantages Britain gained from its expanding industries. Exporting the Revolution was going to mean importing British industrial technologies such as the steam engine and new means of organizing the workforce. Carnot was an engineer and a savant in his own right as well. His *Essai sur les Machines en General* of 1783 and *Principes Fondementaux de l'Equilibre et du Mouvement* of 1803 offered a general theory of the working of machines. He was particularly known for his researches on the work done by waterwheels, linking the work done by the turning wheel to the fall of water between two different levels.

Lazare's son, Sadi Carnot, born in 1796, was therefore well placed to develop an interest in work and engines and to recognize their importance to the French Republic. Sadi was educated by his father until the age of sixteen, when he entered the prestigious École Polytechnique in 1812. By the time he was approaching graduation in 1814, however, Paris was under siege and the Napoleonic regime was rapidly coming to an end. He joined the Corps of Engineers and remained an army officer for most of the rest of his life. Following the restoration of the French monarchy, Lazare Carnot was exiled and Sadi Carnot found himself laboring under the stigma of a now infamous family name. In 1820 he was retired on half pay; he settled in Paris, where he moved on the fringes of philosophical circles, attending lectures at the Sorbonne, the École des Mines, and elsewhere. He played a leading role in the Association Polytechnique, a society of former students from the École Polytechnique with an interest in popular scientific education. Barred from elevation in the ranks or from public office as a result of his unfortunate family connections, he had plenty of time on his hands.

When Sadi Carnot visited his father in exile, Lazare told his son: "If real mathematicians were to take up economics and apply experimental methods, a new science would be created—a science which would only need to be animated by the love of humanity in order to transform government."[3] Carnot spent much of his time traveling through France and the rest of Europe, taking advantage of his opportunities to study industrial organization and practical economics by visiting factories. He made himself expert on the economics of industrializing society and on the machines that operated Europe's factories. The result of all this, coupled with his interest in popular scientific education, was a small pamphlet, *Reflexions sur la Puissance Motrice du Feu*, published in 1824. The book was about heat engines, or more particularly, the steam engine, which already seemed "destined to produce a great revolution in the civilized world" and would "afford to the industrial arts a range the extent of

---

[3] Quoted in S. Carnot, *Reflections on the Motive Power of Fire*, ed. E. Mendoza, xii.

which can scarcely be predicted."[4] Carnot wanted to analyze the heat engine—to find out how it operated, how heat produced work, and what the limits of its efficiency might be. This was to be his contribution to applying the experimental method to economics.

Carnot regarded heat as central to the operations of the natural economy. Nature was an "immense reservoir" of heat that could be regarded as responsible for a whole range of phenomena, from the agitations of the atmosphere to earthquakes and volcanic eruptions. To understand the ways in which heat acted to produce such different kinds of movements, Carnot argued that the problem needed to be expressed in as general a way as possible. The problem with previous analyses was that they had been too specific—too wedded to particular mechanisms. The result was that it became difficult to recognize the general laws and principles underlying the phenomena. The mechanical theory—Newton's laws of motion—could be used to analyze those machines that were put in motion by sources of power other than heat. In those cases "all imaginable movements are referred to these general principles, firmly established, and applicable under all circumstances." This was what was wanted for heat engines as well. "We shall have it," argued Carnot, "only when the laws of physics shall be extended enough, generalized enough, to make known beforehand all the effects of heat acting in a determined manner on any body."[5]

Carnot started, nevertheless, with a specific analysis, following the steam engine through its cycle of operations. "What happens in fact in a steam-engine actually in motion? The caloric developed in the furnace by the effect of the combustion traverses the walls of the boiler, produces steam, and in some way incorporates itself with it. The latter carrying it away, takes it first into the cylinder, where it performs some function, and from thence into the condenser, where it is liquefied by contact with the cold water which it encounters there. Then, as a final result, the cold water of the condenser takes possession of the caloric developed by the combustion. It is heated by the intervention of the steam as if it had been placed directly over the furnace. The steam is here only a means of transporting the caloric. It fills the same office as in the heating of baths by steam, except that in this case its motion is rendered useful."[6] This was the crucial fact for Carnot. What mattered in a steam engine—and in any other kind of heat engine for that matter—was the movement of caloric from a hot to a cold body, not its consumption. It was this movement

---

[4] Ibid., 3–4. [5] Ibid., 6. [6] Ibid., 6–7.

that produced work. "The production of motive power is then due in steam-engines not to an actual consumption of caloric, but *to its transportation from a warm body to a cold body*, that is, to its reestablishment of equilibrium—an equilibrium considered as destroyed by any cause whatever, by chemical action such as combustion, or by any other."[7]

Carnot's conclusion was that "[w]herever there exists a difference of temperature, wherever it has been possible for the equilibrium of the caloric to be re-established, it is possible to have also the production of impelling power."[8] Indeed, work could be carried out only if there were a difference in temperature. If all the Universe were at the same temperature, there could be no flow of caloric and consequently no work could be performed. The question then arose of the exact relationship between work and heat: "Is the motive power of heat invariable in quantity, or does it vary with the agent employed to realize it as an intermediary substance, selected as the subject of the action of the heat?"[9] Carnot had established that a temperature difference allowed work to be done; he also argued that the situation could be reversed: "wherever we can consume this power, it is also possible to produce a difference of temperature, it is possible to occasion destruction of equilibrium in the caloric."[10] The question he aimed to answer was whether the amount of work produced by the flow of caloric from a higher to a lower temperature was the same in all cases as the amount of work required to produce that difference of temperature in the first place. There was a distinct analogy between Sadi Carnot's model of caloric doing work by flowing from one temperature level to another lower one and his father Lazare's analysis of the work done by water turning a waterwheel while flowing from a higher level to a lower.

Sadi Carnot argued that the motive power produced by the fall of caloric from one temperature level to another could never exceed the amount of work that would be required to produce that temperature difference. Otherwise perpetual motion would be possible—a proposition that he, like all respectable late eighteenth- and nineteenth-century natural philosophers, regarded as absurd. The bulk of his pamphlet was devoted to detailed calculations and illustrations to demonstrate the general principle that "[t]he motive power of heat is independent of the agents employed to realize it; its quantity is fixed solely by the temperatures of the bodies between which is effected, finally, the transfer of the caloric."[11] He was emphatic, nevertheless, that the ideal would never in practice be attainable. The point of his work was in the end both pragmatic and socially progressive—to put the theory of how to produce work from heat at the disposal of France. "To know how to appreciate in each case, at their true value, the considerations of convenience and economy which may present themselves; to know how to discern the more important of those which are only secondary; to balance them properly against each other, in order to attain the best results by the simplest means: such should be the leading characteristics of the man called to direct, to co-ordinate the labours of his fellow men, to make them co-operate towards a useful end, whatsoever it may be."[12]

Carnot's treatise was formally presented to the French Académie des Sciences by his friend the engineer and veteran of Napoleon's Egyptian campaign, Pierre Simon Girard. It was not well received. Few members of the elite academy regarded Carnot's *Reflexions* as being in the least germane to their concerns. Girard made other efforts to bring his friend's work to public attention as well. Writing in the prorepublican *Revue Encyclopédique* he averred that "Monsieur Carnot is not afraid of tackling difficult questions; and in this first production he shows himself capable of going into a matter which has become today one of the most important with which theoreticians and physicists can occupy themselves."[13] Among engineers, anxious to exploit his findings concerning ways of maximizing the efficiency of heat engines of various kinds, Carnot's work was better thought of. Academicians, however, regarded his arguments as long-winded, poorly formulated, and frequently incorrect. Carnot's work disappeared almost without trace, particularly following his early death from cholera in 1832. It was hardly surprising that when William Thomson, visiting Paris two decades after its publication, searched high and low for a copy of the *Reflexions*, he could not find a copy, nor even a bookseller who had ever heard of it.

One Frenchman who did pay attention to Carnot's work, however, was the engineer and mathematician Émile Clapeyron. Unsurprisingly, Clapeyron shared many of Carnot's broader interests and concerns. He was a graduate of the prestigious École Polytechnique who had published extensively on the organization of public projects and popular technical education, as well as on technical engineering matters. He had worked in Russia with the French engineer Gabriel Lamé during the 1820s before

[7] Ibid., 7.

[9] Ibid., 8.

[9] Ibid., 9.

[10] Ibid.

[11] Ibid., 20.

[12] Ibid., 59.

[13] Ibid., xiii.

returning to France in 1830. In 1834, he published a paper in the *Journal de l'École Polytechnique* entitled "Memoir on the Motive Power of Heat." Here he set out essentially to translate Carnot's work into the abstract mathematical language familiar to the French academic elite. Intriguingly, as well, he expressed Carnot's findings in terms of indicator diagrams: effectively graphs of pressure against volume. They had originally been developed by James Watt as a way of determining the work done by his improved steam engines and were a closely guarded trade secret. Clapeyron had possibly encountered them in Russia, where they were used by Boulton and Watt engineers building steam engines for Russian manufacturers under license. They provided in any case a striking and easily accessible way of representing Carnot's theories.

Studying and improving the efficiency of steam engines was certainly a matter of ongoing concern among French engineers, anxious to find ways of placing their industries on a par with those of their old enemies across the English Channel. The steam engineer Marc Séguin's *De l'Influence des Chemins de Fer* (1839) discussed matters pertaining to steam engine efficiency at some length. Later in the century, Séguin was to point to this publication as containing an early expression of the principle of the equivalence of heat and work. A mark of the importance increasingly accorded such matters by the French government was the award by the Ministry of Public Works of financial support to Victor Regnault—one of the rising stars of French physics during the 1830s—to carry out extensive experimental research on steam engine efficiency. Regnault embarked on a systematic effort to redetermine experimentally all the data that might be required. The task on which he set out was enormous. The results of his endeavors were not published in full until 1870. In the meantime, however, Regnault's Paris laboratory became one of the premier sites in Europe for the experimental investigation of the science of work.

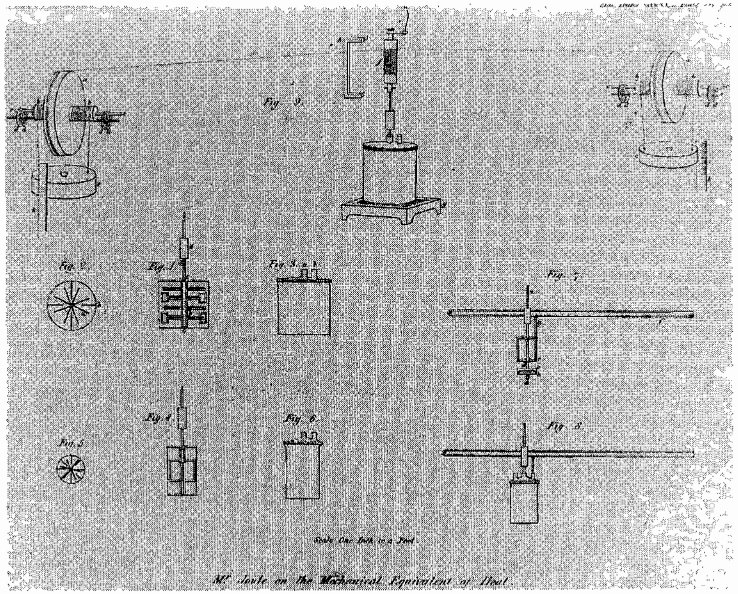
French concern with the science of work, like French science more generally, largely revolved around the state. During the revolutionary and Napoleonic wars and later in the century in terms of commercial rivalry, finding ways of improving the productivity of French industry were seen as an important national imperative. Not only national economic productivity, but national pride—and during the wars, national survival as well—depended on putting science at the state's service. Sadi Carnot's work, straddling the permeable boundary between economics and physics, was an effort to bring abstruse natural philosophy to bear on a very practical question—how to make steam engines work better. The aim of such improvement was to enhance economic productivity, to increase the amount of work available, and in the end enhance the well-being of mankind. In that sense at least, Sadi Carnot's *Reflexions* was an eminently Republican text. It was meant as an example of the way in which physics could be a matter of real, tangible public benefit. It was also firmly technocratic in its vision. The answer to France's (and society's) ills lay in the hands of technical experts, prepared and willing to put their knowledge of nature at the service of the state.

The Culture of Dissipation

Britain in the early decades of the nineteenth century was a rapidly industrializing country. Towns that had been little more than villages a few decades earlier were in the process of being transformed into sprawling cities, their populations booming with the creation and expansion of new industries. In cotton mills, factories, and mines throughout the country, the steam engine and the division of labor were proving the foundation of unprecedented economic expansion. A new culture was being forged as well in these industrial towns and cities. The self-made men who ruled the roost in these new urban conglomerations were a very different breed from the old aristocracy and professions that still dominated the metropolis and the country's political life. Having pulled themselves up by their bootstraps, they valued self-help and hard work. They abhorred waste and inefficiency. The new industrialists regarded the single-minded pursuit of wealth as a perfectly respectable goal in its own right. Their politics was largely liberal and free-market, their religion nonconformist, though as the century progressed they veered more and more towards Toryism and the Anglican Church. Many of this new breed admired science, as long as it could be put to practical use for the benefit of mankind and the size of their purses. In particular, the science they valued also valued work, efficiency, and the diminution of waste.

Manchester was a major center for this new self-confident provincial culture. Its population of more than 300,000 in the 1830s was more than ten times its size a century earlier. It was an important center for the cotton industry that produced so much of the country's newfound manufacturing strength. It also boasted a flourishing Literary and Philosophical Society, founded as early as 1781 as a forum through which to express the cultural and philosophical aspirations of its rising middle classes. When James Prescott Joule, a successful brewer's son from Salford, a suburb of Manchester, started experimenting on engine efficiency in the late 1830s, the city already had a thriving scientific culture. Joule's tutor was the eminent chemist John Dalton, and he was soon collaborating with the electrician William Sturgeon, recently moved from London to be superintendent of the Royal Victoria Gallery for the Encouragement and Illustration of Practical Science. Joule's early experiments were on the newly invented electromagnetic engines. As we saw previously, however, he rapidly became discouraged with this work and expanded his researches to look at the question of engine efficiency more generally. He was soon fascinated by the relationship between heat and work and in trying to find ways of maximizing the production of motive power from heat.

Joule experimented diligently throughout the first half of the 1840s. His particular concern was to find ways of quantifying the relationship between heat and work—the mechanical equivalent of heat, as he called it. He argued that his experiments were conclusive proof that heat was not a particular substance—caloric—but a form of motion, or *vis viva*. With his brewing background, Joule was well versed in the precision thermometric measurements required to ground such ambitious claims. His potential audience at the Royal Society, however, was reluctant to accept his experimental efforts, rejecting his work for publication in their *Philosophical Transactions*. They did not trust this provincial, whose links were with Sturgeon and the unsavory London Electrical Society rather than with elite gentlemen of science. Joule persevered throughout the 1840s, refining his techniques and his experiments. In 1845 he presented the annual meeting of the British Association for the Advancement of Science with the results of what is now known as his paddle wheel experiment (figure 5.2). In this experiment, weights attached through pulleys to a paddle wheel enclosed in a container of water caused the paddle wheel to rotate as the weights fell. Joule argued that the experiment showed how "the force spent in revolving the paddle-wheel produced a certain increment in the temperature of the water." In other words, the motion of the weights was transformed into heat in the water. This conversion could be accurately measured: "when the temperature of a pound of water is increased by one degree of Fahrenheit's scale, an amount of *vis viva* is communicated to it equal to that acquired by a weight of 890 pounds after falling from the altitude of one foot."[14] Once again, little attention was paid to Joule's work on this occasion, but when he presented a new version of his experiments to the BAAS two years later in Oxford in 1847, the audience contained a very receptive pair of ears belonging to the ambitious young Glaswegian natural philosopher, William Thomson.



5.2 James Prescott Joule's famous paddle wheel experiments, demonstrating the mechanical equivalent of heat.

Like Manchester, Glasgow in the first half of the nineteenth century was a thriving industrial citadel, profiting both from the cotton mills in its hinterland and the shipbuilding industry of the city itself. Like Manchester also, it had an active scientific culture, based around the university and the Glasgow Philosophical Society, where hardheaded industrialists, businessmen, engineers, and sympathetic university academics rubbed shoulders and shared values based on work and efficiency. The Thomson family had moved to Glasgow from Belfast—another center of industry and self-help Presbyterian values—when James Thomson, the father, was appointed professor of mathematics at Glasgow College in 1832. Like their father, William Thomson and his older brother James shared in the Glasgow ethos, inherited from the eighteenth-century Scottish Enlightenment, of hard work, religious toleration, and self-discipline. James Thomson the younger, after his graduation from Glasgow College in 1840, aimed at a career in engineering, having been a passionate inventor in his youth, trying to find ways of minimizing the waste and

---

[14] J. P. Joule, "On the Mechanical Equivalent of Heat," *Reports of the British Association for the Advancement of Science*, 1845, 15: 31.

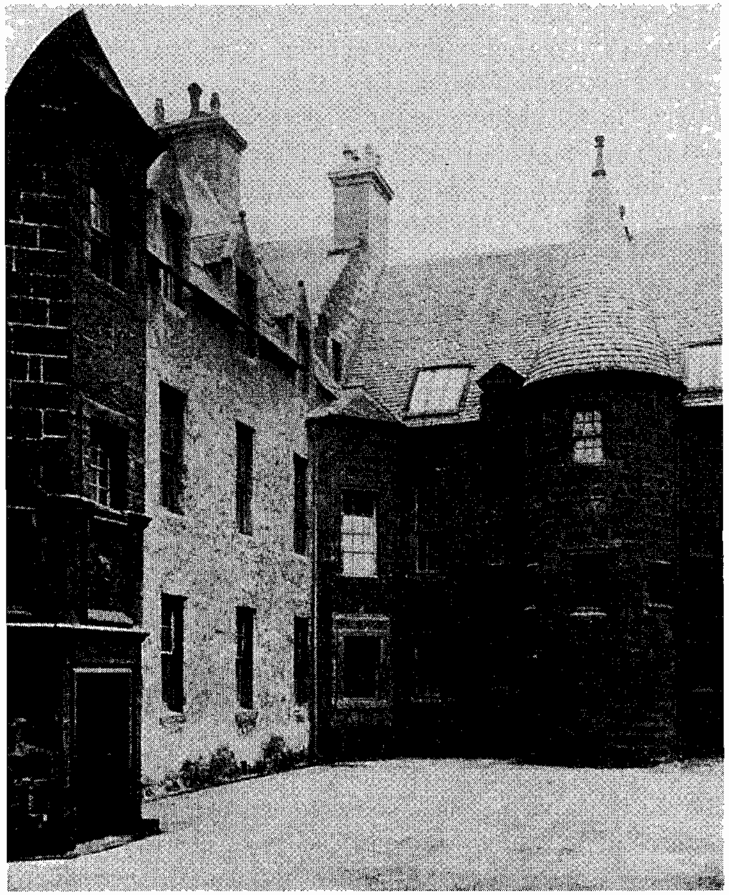
maximizing the economic efficiency of engines. In 1843 he was apprenticed to William Fairbairn's machine-making engineering firm. William Thomson, with his talent for mathematics, on the other hand, following his own graduation from Glasgow a year later, headed for a second degree in Cambridge and the mathematical Tripos.

As we have already seen, Cambridge by the 1840s was probably one of the best places in Europe at which to acquire a rigorous mathematical training. The analytical revolution of two decades earlier had transformed the syllabus. The system of tutors guaranteed personal attention and plenty of opportunity for practice. Thomson's tutor was William Hopkins of St. Peter's College, known for his reliable production of high wranglers. Thomson did well, graduating second wrangler and first Smith's prizeman in 1845. Following his graduation, he visited Paris, where as well as searching unsuccessfully for Carnot's *Reflexions* (and making do with Clapeyron instead) he worked with Victor Regnault in his physics laboratory. Given Regnault's concern with steam engines, this was ideal further training for a hopeful natural philosopher with Thomson's interests in work, efficiency, and the annihilation of waste. The experience provided him with a thorough grounding in experimental practice to complement the mathematical expertise he had acquired at Cambridge. The experience was soon to be put into practice when later the same year he was appointed to the vacant chair of natural philosophy at Glasgow (figure 5.3). Throughout his time at Cambridge and after, William and his brother had been in constant correspondence over the vexed issue of heat, work, and waste. The issue was to vex Thomson for several decades to come.

James Thomson had encountered the Carnot-Clapeyron theory of the motive power of heat during his engineering training. As he explained it to his brother, he had learned that "during the passage of heat from a given state of intensity to a given state of diffusion a certain quantity of mechanical effect is given out whatever gaseous substances are acted on, and that no more can be given out when it acts on liquids or solids."[15] What concerned both brothers was the waste involved in the process in practice. A water mill wasted work by spillage of water from the wheel buckets; a steam engine wasted work by releasing steam or water when it was still hotter than its surroundings. Following Carnot, they both believed that caloric, or heat, was conserved during the production of work. Their problem was in how to get the most out of it. Increasingly, they

---

[15] Quoted in C. Smith, *The Science of Energy*, 42.



5.3 William Thomson's teaching laboratory at Glasgow. The three windows on the left on the ground floor are those of the physical laboratory; the three above belong to the apparatus room. Entrance to both rooms was through the door in the pentagonal tower on the left.

regarded the Carnot-Clapeyron theory, in which work was the result of caloric flowing from one temperature to a lower one, as the best available account of the workings of engines. William Thomson's experiments in Glasgow on a Stirling air engine seemed to confirm this view. This was why he found Joule's claim at the Oxford meeting of the BAAS in 1847, of experimental proof that mechanical work was the result of an absolute loss of heat, deeply puzzling.

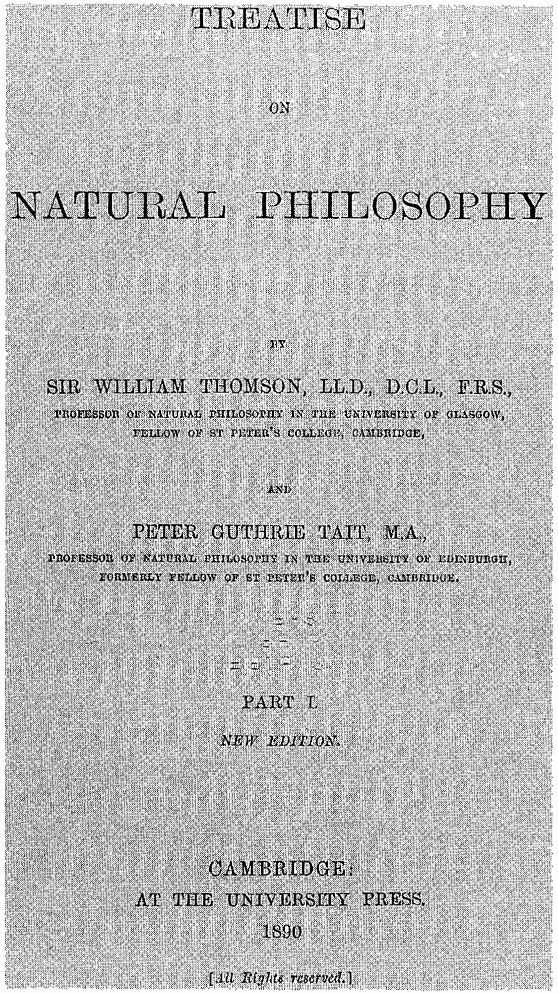
Thomson expressed his conundrum in trying to reconcile Carnot and Joule in a famous footnote to his "Account of Carnot's Theory of the

Motive Power of Heat," first read to the Royal Society of Edinburgh in 1849: "When 'thermal agency' is thus spent in conducting heat through a solid, what becomes of the mechanical effect which it might produce? Nothing can be lost in the operations of nature—no energy can be destroyed. What effect then is produced in place of the mechanical effect which is lost? A perfect theory of heat imperatively demands an answer to this question; yet no answer can be given in the present state of science."[16] If work were simply the result of heat falling from one temperature level to another, as Carnot suggested, then what happened to the work that might have been produced if there was no engine there for it to operate on? Conversely, if, as Joule argued, the production of work required an absolute loss of heat, where did the heat go in cases where no useful work was apparently being done, as in the case of simple heat conduction? In 1849, when Thomson presented his account of Carnot's theory to the Royal Society of Edinburgh, he still had no answer to these pressing questions.

Within a few years, however, Thomson thought he had solved the problem. In a series of papers entitled "On the Dynamical Theory of Heat," presented to the Royal Society of Edinburgh between 1851 and 1855, he laid the framework of the new science of heat he would call thermodynamics. His theory rested on two central propositions. The first one, derived from Joule, stated: "When equal quantities of mechanical effect are produced by any means whatever from purely thermal sources, or lost in purely thermal effects, equal quantities of heat are put out of existence or are generated."[17] In other words, he had fully accepted Joule's assertion of the mutual convertibility of heat and work. Thomson's second proposition rested on his reading of Carnot. He stated: "If an engine be such that, when it is worked backwards, the physical and mechanical agencies in every part of its motions are all reversed, it produces as much mechanical effect as can be produced by any thermo-dynamic engine, with the same temperatures of source and refrigerator, from a given quantity of heat."[18] He had abandoned his earlier commitment to Carnot's insistence that caloric, or heat, be conserved during this process. He concluded that in any process of heat transfer that did not fulfill Carnot's criterion of perfect reversibility—in other words, in any real engine—there was "an absolute loss of mechanical energy available to man."[19]

[16] Quoted ibid., 94.
[18] Quoted ibid., 110.
[19] Quoted ibid., 107.
[19] Quoted ibid., 124.

Thomson's universe now had a sense of direction. It was a universe in which the capacity for doing useful work was continually being lost. Carnot's perfectly reversible engine was an ideal that could not exist in the real world. Every time a real engine operated, friction, bad lubrication, imperfect insulation, and any number of other effects colluded to dissipate energy. These were not just facts of life, they were facts of the Universe. Any natural process involved an inevitable loss of heat that



TREATISE

ON

NATURAL PHILOSOPHY

BY

SIR WILLIAM THOMSON, LL.D., D.C.L., F.R.S.,
PROFESSOR OF NATURAL PHILOSOPHY IN THE UNIVERSITY OF GLASGOW,
FELLOW OF ST PETER'S COLLEGE, CAMBRIDGE,

AND

PETER GUTHRIE TAIT, M.A.,
PROFESSOR OF NATURAL PHILOSOPHY IN THE UNIVERSITY OF EDINBURGH,
FORMERLY FELLOW OF ST PETER'S COLLEGE, CAMBRIDGE.

PART I.

NEW EDITION.

CAMBRIDGE:
AT THE UNIVERSITY PRESS.
1890

[*All Rights reserved.*]

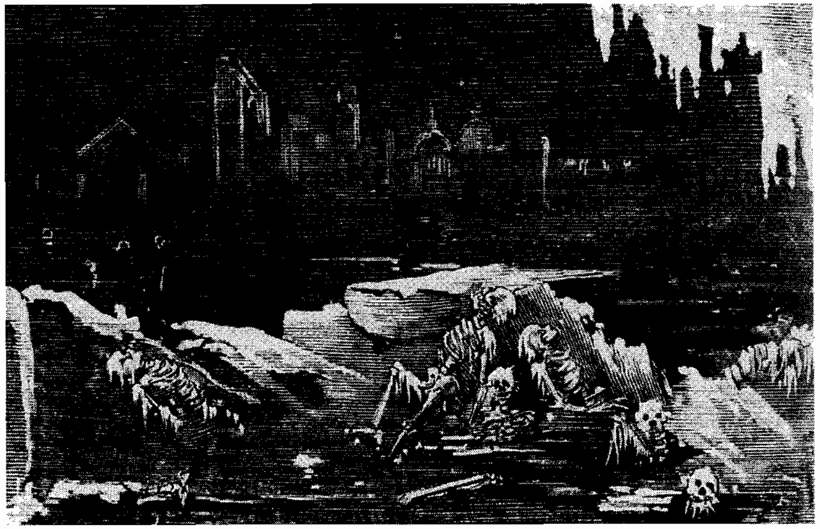
5.4 The title page of William Thomson and Peter Guthrie Tait, *Treatise on Natural Philosophy*.

might have been converted into useful work by falling between two temperature levels. Once that capacity to do work had been lost it could not be recovered. There was a strong moral imperative implicit in all of this. If work was continuously being lost, it behooved the canny operator to take advantage of as much of it as he could while it remained available. This was the worldview shared by Thomson, Joule, and an increasing number of other engineers and natural philosophers from nonconformist, industrial backgrounds. Men such as W. J. Macquorn Rankine, a Clydeside engineer and later professor of civil engineering and mechanics at Glasgow, and Peter Guthrie Tait (with whom Thomson wrote *Treatise on Natural Philosophy*), Cambridge wrangler from an Edinburgh banking family and professor of mathematics at Queen's College Belfast, before returning to Edinburgh as professor of natural philosophy in 1860, played key roles in helping Thomson during the 1850s and 1860s to further articulate this new science of thermodynamics, based on the mechanical equivalent of heat and the universal tendency towards dissipation (figure 5.4).

For Thomson and his coworkers in Britain, one of the major virtues of the new science of thermodynamics was precisely the way in which it provided the universe with a sense of direction. Man could direct the operations of nature but could not reverse them. The Universe had a beginning and—more importantly—it had an end. There would come a time when all heat had been dissipated. The energy would all still be there—nothing would have been lost—but the universe would be at a uniform temperature, and without heat transfer from higher to lower temperatures no work could be done and the universe would be at a standstill. This "heat death of the Universe" evoked powerful images (figure 5.5). H. G. Wells made good use of the scenario in the closing pages of *The Time Machine*. Moving forward through time, Wells's traveler eventually arrived at a desolate future: "The sky was no longer blue. North-eastward it was inky black, and out of the blackness shone brightly and steadily the pale white stars. Overhead it was a deep Indian red and starless, and south-eastward it grew brighter to a glowing scarlet where, cut by the horizon, lay the huge hull of the sun, red and motionless."[20] It was a scene that never changed, since the Earth had long since ceased rotating on its axis. Moving another thirty million years into the future, the traveler witnessed an eclipse of the sun over a now lifeless planet: "The darkness grew apace; a cold wind began to blow in freshening gusts from the east, and the showering white flakes in the air increased in number.

---

[20] H. G. Wells, *The Time Machine* (1895; reprint, London: Everyman Library, 1995), 73.



5.5 The end of the world and the heat death of the Universe as envisaged by Camille Flammarion in 1893.

From the edge of the sea came a ripple and whisper. Beyond these lifeless sounds the world was silent. Silent? It would be hard to convey the stillness of it. All the sounds of man, the bleating of sheep, the cries of birds, the hum of insects, the stir that makes the background of our lives—all that was over."[21] It was a graphic description of Thomson's universe, though the materialist Wells provided his book with a cheeky evolutionist narrative that would have left Thomson fuming.

Indeed Thomson, and his antimaterialist allies regarded thermodynamics as a powerful weapon with which to counter Darwinian evolution. In a series of papers in the early 1860s, appearing shortly after the publication of Darwin's *Origin of Species* in 1859, Thomson argued that thermodynamics clearly demonstrated that natural selection was wrong. The Sun could not have been provided with an infinite store of energy nor was there any obvious chemical or mechanical source of energy with which it could be replenished. The Sun's heat had therefore to be finite. There were only two possible hypotheses concerning the sun's origins: "The sun must . . . either have been created as an active source of heat at some time of not immeasurable antiquity, by an over-ruling decree; or the heat which he has already radiated away, and that which he still

---

[21] Ibid., 75.

possesses, must have been acquired by a natural process, following permanently established laws. Without pronouncing the former supposition to be essentially incredible, we may safely say that it is in the highest degree improbable, if we can show the latter to be not contradictory to known physical laws. And we can do this and more, by merely pointing to certain actions, going on before us at present, which, if sufficiently abundant at some past time, must have given the sun heat enough to account for all we know of his past radiation and present temperature."[22] Thomson's calculations and his figures provided him with a conservative estimate of the age of the sun: "It seems, therefore, on the whole most probable that the sun has not illuminated the earth for 100,000,000 years, and almost certain that he has not done so for 500,000,000 years. As for the future, we may say, with equal certainty, that inhabitants of the earth cannot continue to enjoy the light and heat essential to their life, for many million years longer, unless sources now unknown to us are prepared in the great storehouse of nature."[23] Similar calculations placed strict limits on the possible age of the Earth, making Darwin's estimate of 300,000,000 years for the "denudation of the Weald" alone, for example, appear hopelessly optimistic.

The dynamical theory of heat, in Thomson's articulation, was very much a product of a Scottish and northern English industrial sensibility. Its creators came from backgrounds that valued hard work, self-discipline, and thrift and abhorred dissipation and waste. This is what the dynamical theory was about. Waste was endemic—an unavoidable feature of life built into the very fabric of the universe. Waste could be minimized, however, even if could not be eliminated entirely, by careful and disciplined attention. It was a theory that arose from very pragmatic considerations. Joule's initial interest in engine efficiency had come about as a result of his experiments to maximize the efficiency of the electromagnetic engines enthused over by his fellow electricians in the London Electrical Society. His concerns about the practical improvement of engines led him to consider the relative advantages of work from different sources. Thomson had been motivated by the equally practical concern he shared with his brother to find a theory that could be exploited to minimize the waste of power in steam engines. These concerns mattered to them because they were concerns that mattered to the cultures they inhabited. They wanted to put natural philosophy to work so that it could minimize the wastage of the industrial society they inhabited and increase its profits. The thermodynamic model also had the virtue of recapturing the idea of progression from those they regarded as dangerous materialists.

The German Science

As we saw earlier, major changes were afoot in German natural philosophy during the second quarter or so of the nineteenth century. A new generation of practitioners were anxious to dissociate themselves from what they regarded as the metaphysical excesses of the previous generation's *Naturphilosophie*. In Prussia in particular, major educational reforms during the early years of the century had greatly expanded the number of students attending university. Unlike at the old English universities, research was increasingly starting to be considered part of a professor's duties at these new German institutions. The new University of Berlin, opened in 1809, had close links with the Berlin Academy of Sciences. It was entirely funded by the Prussian state. By midcentury, the reforms were coming to fruition. The population was educated to an unprecedented degree. These were not disinterested initiatives on the part of the Prussian state. Education, and technical education in particular, was seen as the key to industrialization and modernization. This state-sponsored expansion of the educational system, in turn, provided opportunities at all levels to the new generation of hopeful natural philosophers. It provided them with the resources to reshape German science in their own image and to forge it into a central feature of nineteenth-century German notions of statehood. The science of work was crucial here as well. It was to prove an indispensable linchpin in the process of refounding German science on a materialist, rationalist (and nationalist) basis.

While his English, French, and Scottish contemporaries became engaged in constructing a science of work as a product of their concern with the steam engine and its efficiencies, the German doctor Julius Robert Mayer, as befitted his profession, was more concerned with the human body. Born the son of an apothecary in the city of Heilbronn in the kingdom of Württemberg in 1814, Mayer studied medicine at the University of Tübingen during the early 1830s. In autobiographical sketches written later in life, he maintained that as a child he had been fascinated by machinery and the quest for a perpetual motion engine. Having completed his medical degree at Tübingen by 1838, he went to Amsterdam, where, having completed the relevant examinations, he enlisted as a ship's doctor

---

[22] W. Thomson, *Popular Lectures and Addresses* (London, 1889), 1: 363–64.

[23] Ibid., 1: 368.

with the Dutch East India Company. After spending some time in Paris, he embarked from Rotterdam aboard the ship *Java*, sailing for the Dutch East Indies in 1840. In the course of his duties as ship's doctor, he became aware of the unusual color of the venous blood of his shipmates. It was unusually red, appearing more like arterial than venous blood. The implication was that the heat of the tropics bore some relationship to the oxygenation of the blood. He eventually concluded that in the tropical heat the body expended less effort in maintaining its internal heat and that as a result less oxidation took place in the blood. It was to this observation that he attributed his interest in heat, work, and the body.

Back in Heilbronn in 1841 and embarking on a medical practice on dry land Mayer tried to interest others in his speculations concerning heat and work. He tried unsuccessfully to publish his work in the prestigious *Annalen der Physik und Chemie*, edited by Johann Christian Poggendorff. In his first published work, "Remarks on the Forces of Inanimate Nature," published in the *Annalen der Chemie und Pharmacie* in 1842, he argued for a relationship between "fallforce," motion, and heat: "We can make clear to ourselves the natural connection existing between fallforce, motion and heat in the following way. We know that heat appears when the individual massy particles of a body move closer to each other; compression produces heat; now, what holds for the smallest massy particles and the smallest spaces between them must well also apply to large masses and measurable spaces. The descent of a weight is a real reduction in the volume of the earth, and thus must certainly stand in connection with the heat that thereby appears; this heat must be exactly proportional to the size of the weight and its (original) distance. From this consideration one is led quite easily to the above-discussed equation of fallforce, motion, and heat."[24] Such hypothetical arguments were unlikely to gain favor with the new leaders of German science, committed to precision in experiment and language.

Mayer attributed to his voyage on the *Java* the discovery "that motion and heat are only different manifestations of one and the same force, and that consequently motion or mechanical work and heat, which had hitherto mostly been regarded as entirely disparate things, must also be able to be converted and transformed into one another."[25] He had a specific figure for the quantitative relationship between motion and heat in mind as well, derived from published figures for the heating of air by

---

[24] Quoted in K. Caneva, *Robert Mayer and the Conservation of Energy*, 24–25.

[25] Quoted ibid., 28.

compression. He asserted that "the fall of a given weight from a height of around 365 meters corresponds to the heating of an equal weight of water from 0° to 1°."[26] Mayer's work had little impact at the time, though it presumably impressed the eminent chemist, Justus Liebig, who edited the *Annalen der Chemie und Pharmacie*. Mayer had little to say about the matters that concerned other enthusiasts for the science of work. His theories were couched in speculative and obscure terms as well. To many of his potential audience he must have read like a *Naturphilosoph* himself, although he roundly repudiated any such connection. He made clear, moreover, that he was no materialist—and materialism was very much in vogue among the new generation of German natural philosophers.

Like his near contemporary Mayer, Hermann von Helmholtz approached the science of work from a medical perspective as well. Born in 1821, the son of a Prussian *Gymnasium* teacher, Helmholtz studied medicine at the University of Berlin, with the Prussian army paying his way. In return for four years of medical education he undertook to spend the next eight years serving the army as a medical officer. He therefore spent the years between 1843 and 1848 as a staff surgeon based at Potsdam until his patron, the eminent anatomist and physiologist Johannes Müller, engineered his early discharge from the military and secured for him in 1849 a position as associate professor of physiology at the University of Königsberg. During his years in the army, Helmholtz had been a prolific publisher on physiology, having carried out experiments on, among other things, the role of heat in muscle physiology. He was part of an ambitious young coterie of experimental physiologists, including Emil du Bois Reymond and Carl Ludwig, who were anxious to turn physiology into a robustly materialist experimental science, purged of dubious metaphysical trappings like the life force. For this group of physiologists anything that happened in the body, like anything that happened in the steam engine, should be measurable and strictly quantifiable.

In 1847, Helmholtz published his latest contribution to this campaign—*Über die Erhaltung der Kraft* (On the Conservation of Force). The essay was privately published in pamphlet form. Like Mayer before him, Helmholtz had attempted to interest Poggendorff and his prestigious *Annalen der Physik*, but had also been rebuffed. Helmholtz's physiological work had been aimed at showing how the heat of animal bodies and their muscular action could be traced to the oxidation of food—their fuel. In this he was following in the footsteps of Liebig, who had pioneered

---

[26] Quoted ibid., 25.

research into the connections between the chemistry of nutrition and vitality. Where Carnot, Joule, and Thomson had been concerned to identify the origins of work in the steam engine, Helmholtz was concerned with its origins in the human engine. One of Helmholtz's particular concerns was to show that the supposition of a vital living force violated the principle of the impossibility of perpetual motion, since a living force would in principle be producible out of nothing. All the work produced by a human body, like all the work done by a steam engine, had to be accounted for. In his essay Helmholtz posited a purely mechanical universe in which the exact quantitative relationship of different forces to each other was susceptible of mathematical demonstration.

For Helmholtz, there was an obvious connection between human and machine work. "The idea of work is evidently transferred to machines from comparing their performances with those of men and animals, to replace which they were applied. We still reckon the work of steam-engines according to horse-power."[27] He traced the origins of the science of work to eighteenth-century efforts to produce mechanical automata that could replace living beings. This focused attention on the forces that animated living bodies and their origins. This was then the basis for comparison between humans and machines in terms of the sources of the work they performed. The conclusion was the principle of the conservation of force: "We cannot create mechanical force, but we may help ourselves from the general storehouse of Nature. The brook and the wind, which drive our mills, the forest and the coal-bed, which supply our steam-engines and warm our rooms, are to us the bearers of a small portion of the great natural supply which we draw upon for our purposes, and the actions of which we can apply as we think fit. The possessor of a mill claims the gravity of the descending rivulet, or the living force of the moving wind, as his possession. These portions of the store of Nature are what give his property its chief value."[28] Nature, from this perspective, was a storehouse of work that could be exploited through various mechanisms, including the human body and the steam engine.

While Mayer and Helmholtz were moved by physiological considerations to investigate the science of work, Helmholtz's fellow Prussian, Rudolf Clausius, approached the issue, like his British and French

contemporaries, from the perspective of the steam engine. Born in 1822, he entered the University of Berlin in 1840, studying mathematics and the natural sciences. After qualifying as a *Gymnasium* teacher he remained in Berlin throughout the 1840s, obtaining a doctorate in 1848 with a dissertation on "the light-dispersing and luminous effects of the atmosphere through theoretical considerations,"[29] following in the footsteps of his patron, the physicist Heinrich Gustav Magnus. Following the completion of his doctoral studies, he turned to the study of the motion of gases and elastic bodies. It was this research that focused his attention on the problems of heat and work, through his reading of Regnault's experimental work and of Clapeyron's and others' theories. He was soon appointed as a physics teacher to the Berlin Artillery and Engineering School and as a *Privatdozent* (or tutor) at the University of Berlin. Unlike Mayer and Helmholtz, Clausius was successful in publishing his first venture into the science of work—"On the Moving Force of Heat, and the Laws Regarding the Nature of Heat That Are Deducible Therefrom"—in the *Annalen*. It appeared in 1850.

Clausius's publication was based on his reading of William Thomson's 1849 "Account of Carnot's Theory." His argument was simple: Thomson was mistaken in supposing that Carnot and Joule were necessarily at odds with each other in any crucial respect. It was possible, he argued, to reconcile Carnot's claim that work was the result of heat flowing from one temperature level to another, lower, temperature level, with Joule's assertion that work was the product of conversion from heat. The trick, he claimed, was simply to drop Carnot's assumption that heat was conserved during the process. There was no reason to suppose that the production of work by heat did not require *both* the flow of heat from one temperature level to another *and* the conversion of a certain proportion of the heat into work. As he put it, "It is not at all necessary to discard Carnot's theory entirely, a step which we certainly would find it hard to take, since it has to some extent been conspicuously verified by experience. A careful examination shows that the new method does not stand in contradiction to the essential principle of Carnot, but only to the subsidiary statement *that no heat is lost*, since in the production of work it may very well be the case that at the same time a certain quantity of heat is consumed and another quantity transferred from a hotter to a colder body, and both quantities of heat stand in a definite relation to the work that is

---

[27] H. Helmholtz, "The Interaction of Natural Forces," in D. Cahan (ed.), *Science and Culture*, 20.

[28] Ibid., 29.

[29] Quoted in C. Jungnickel and R. McCormmach, *The Intellectual Mastery of Nature*, 1: 164.

done."[30] This was much the conclusion at which Thomson would arrive in his 1851 paper "On the Dynamical Theory of Heat." Indeed, Thomson's resolution of his dilemma was based on his reading of Clausius's paper.

Clausius worked on refining his theories of heat throughout the 1850s and beyond. Increasingly, as we shall see, he started making explicit links between the theory of heat and the work on gases in motion that had first drawn his attention to the problems of heat and work. Clausius was interested in the kinetic theory of gases—the idea that the large-scale properties of gases could be understood as the results of the small-scale movements of the particles, or molecules, of which the gases were made up. He understood heat to be simply an effect of the motion of such particles—hot gases were made up of fast-moving particles, colder gases were made up of slower particles. Work, then was the result of "the alteration in some way or another of the arrangement of the constituent molecules of a body."[31] In 1865, Clausius introduced a new word—"entropy"—into his version of the dynamical theory of heat. He could then reformulate the second principle of the dynamical theory of heat as the assertion that the entropy of the universe tends to a maximum.

Both Helmholtz and Clausius made their names with their contributions to the science of work. Not only were they established as key figures in German science, they were as a result of their work on heat players on the international stage as well. Their success and that of those like them in other new-forged disciplines, in attracting attention to their theories, also made German science successful. Throughout the nineteenth-century German laboratories and research institutes were increasingly attractive places of pilgrimage for young scientific acolytes keen to study at the feet of these new masters of physics. The science they produced was self-consciously abstract and rationalist. It was avowedly and deliberately the antithesis of the previous generation's wildly metaphysical *Naturphilosophie*. Arguably, the research tradition forged in mid-nineteenth-century German research institutes might well be regarded as the direct precursor of twentieth-century theoretical physics. It was a tradition that regarded mathematical theorizing about nature as an autonomous activity in its own right. It was becoming clear by the 1860s, however, that this German science that might appear to the casual observer as having so much in common with it, was also the direct antithesis of the new natural

---

[30] R. Clausius, "On the Motive Power of Heat, and on the Laws which can be Deduced from it for the Theory of Heat," 112.

[31] Quoted in C. Smith, *The Science of Energy*, 167.

philosophy that William Thomson and his acolytes in England and Scotland held so dear.

The Statistical Universe

As we have just seen, one of the things that drew Clausius to study heat and the science of work was his interest in the kinetic theory of gases—the idea that gases were made up of large numbers of rapidly moving particles and that their heat was the result of these rapid movements. The idea that heat was a form of motion was not new, of course. Benjamin Thompson, the flamboyant refugee from the American War of Independence, had carried out experiments showing that heat was produced during the process of drilling a cannon bore, which he suggested showed that heat was a form of motion. Sir Humphry Davy came to the same conclusion on the basis of experiments involving the melting of ice by friction. James Prescott Joule regarded his own experiments on the mechanical equivalent of heat as having decisively established that heat was the result of motion. What interested Clausius was the question of just what kind of motion was heat. Was it the result of the internal particles making up a body vibrating, for example? Or was it the result of translational motion from one position to another? Heat might even be the result of particles rotating on their own axes.

Others, of course, had no truck with the idea that heat was a form of motion at all. The fate of two British contributors to discussions of such matters provides a good example of the view's marginality for much of the first half of the century. In 1820, John Herapath, an English journalist and mathematician, submitted a manuscript, "A Mathematical Inquiry into the Causes, Laws, and Principal Phenomena of Heat, Gases, Gravitation, &c," to be read at the Royal Society and published in its *Philosophical Transactions*. Among other things, Herapath in his manuscript offered a mathematical derivation of the ideal gas law (relating the pressure, volume, and temperature of a gas) on the basis that the heat of a gas was proportional to the internal motion of its constituent particles. The paper was rejected. Similarly, in 1845 a young tutor for the East India Company in Bombay, John James Waterston, submitted a paper to the Royal Society, "On the Physics of Media that are Composed of Free and Elastic Molecules in a State of Motion." It was dismissed by John Lubbock, one of the society's referees, as "nothing but nonsense."[32] Half a century later,

---

[32] Quoted in S. Brush, *The Kind of Motion we Call Heat*, 1: 140.

with the kinetic theory of gases well-established, Waterston's manuscript was discovered by Lord Rayleigh in the society's archives, dusted down, published in the *Philosophical Transactions* for 1892 and triumphantly hailed as a British precursor. Herapath's ideas were picked up by James Joule during the course of his own speculations on the origins of heat during the late 1840s. But Joule himself was at the time still a largely obscure figure, and his views attracted little attention.

Clausius's paper "Über die Art der Bewegung, welche wir Wärme nennen" (On the Kind of Motion that we call Heat) was published in the *Annalen* in 1857. In this paper Clausius argued that the heat of a gas must be made up of several kinds of motion on the part of its constituent particles. Particles in a gas must have rotational and vibrational motion as well as translational motion. The total heat of a gas must therefore be proportional to the sum of these motions. On the basis of this model, Clausius could calculate various properties of his hypothetical gas and compare them with the known properties of real gases. Clausius assumed that compared with the volume of a gas as a whole, the volume taken up by the particles themselves was infinitesimally small. He also assumed, for purposes of calculation, that all the particles moved with the same average velocity, which he calculated for different gases as being hundreds, if not thousands, of meters per second. In the face of objections that these figures must be false, since otherwise gases would diffuse far more quickly than they were known to do, Clausius soon abandoned the assumption that the volume of the particles themselves was infinitesimal. Instead he introduced the concept of the "mean free path," or the average distance that a particle could travel in a straight line before colliding with another particle.

Clausius's efforts alerted others to the possibilities of using a dynamical (or kinetic) theory of gases as a way of providing a convincing model of heat and work on a microscopic level. James Clerk Maxwell's "Illustrations of the Dynamical Theory of Gases," published in the *Philosophical Magazine* in 1860, made use of Clausius's concept of the mean free path. But where Clausius had every particle in a gas moving at the same average velocity, Maxwell drew on the science of statistics to allow for a random distribution instead. Nineteenth-century statistics had its origins in the study of populations of people rather than of inanimate objects. Maxwell had become interested in statistical theory as a student at Cambridge, after reading John Herschel's review in the *Edinburgh Review* of Adolphe Quetelet's work on probability. Quetelet was interested in what he called "social physics" and turned to statistics as a way of understanding large

populations. Herschel's review was an effort to bring Quetelet's work to a wider audience and certainly seems to have convinced the young Maxwell, who wrote to his friend Lewis Campbell that "the true logic for this world is the Calculus of Probabilities ... the only 'Mathematics for Practical Men', as we ought to be."[33] This was the logic that he applied about ten years later to understanding the dynamical theory of gases.

Maxwell, in his *Philosophical Magazine* contribution, argued that collisions between the constituent particles of a gas would produce a distribution of velocities rather than leading towards an equalization of velocities. On this basis, he calculated what the statistical law governing the distribution of velocities in a gas might be. He also established the equipartition theorem, arguing that the energy of the particles of a gas was equally distributed among their modes of motion: rotational, translational, and vibratory. The picture of the microscopic world that Maxwell produced was one of particles whizzing haphazardly through space, colliding with each other and bouncing off in random directions. The movements of these individual particles were impossible to predict. Just what these particles were also remained an open question. Like William Thomson, Maxwell toyed with the idea (put forward by Helmholtz) that they were in fact vortices in the ether and that the large-scale properties of matter could in theory be calculated from the characteristics of these vortices. One thing Maxwell was sure of, however. The motions of these particles might be random, but the particles themselves were not. Maxwell not only argued that particles of the same elements of matter were identical, but that their identity was proof of the existence of a divine manufacturer.

Maxwell was keenly aware that the probabilistic nature of his arguments caused problems for the new thermodynamics. In particular, it raised questions about irreversibility and the second law of thermodynamics. He illustrated the problem in a letter to P. G. Tait in 1867 by introducing the idea of an intelligent being who had the ability to change the direction of individual particles of a gas. Maxwell imagined a situation where particles of gas were confined in two partitions, separated by a frictionless sliding door. The particles of gas in each partition would have a distribution of velocities as determined by Maxwell's own distribution law. By opening and closing the door at the appropriate time, the being—"Maxwell's Demon," as William Thomson later baptized him—could change the distribution of velocities, confining the faster particles

---

[33] L. Campbell and W. Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), 143.

to one partition and the slower ones to another. The result would be that the gas in one partition became hotter and the gas in the other became colder—an apparent flow of heat from a cold to a hot body without any work having been carried out on the system, in seeming contradiction to the second law of thermodynamics. Maxwell used the apparent paradox of the demon to raise questions about determinism and the relationship between physical phenomena on the microscopic and the macroscopic scale. What it showed, he argued was that the second law of thermodynamics "has only a statistical certainty."[34]

Maxwell's ideas about interpreting thermodynamic laws statistically were taken up by the Austrian physicist Ludwig Boltzmann. Boltzmann, educated at Linz and at Vienna under the physicist Josef Stefan, was in many ways a typical product of the new style of German physics education. He argued that the laws of thermodynamics could no longer be taken to apply absolutely in the microscopic realm. In particular the second law of thermodynamics, stating that the entropy of the universe was continually increasing, had to be understood as a statistical, rather than a strictly deterministic, generalization. In other words it was possible, if not very likely, that under certain circumstances entropy could decrease. His ideas were, to put it mildly, controversial. Boltzmann clashed repeatedly during his career with opponents such as the physicist and philosopher Ernst Mach, who argued that Boltzmann's ideas made nonsense of the whole enterprise of physics. Mach felt that Boltzmann's ideas were excessively metaphysical and went beyond the boundaries of what was observable and therefore knowable in science. Many of his German contemporaries had problems with Boltzmann's insistence on the reality of the atomic theory, which they felt went against current trends towards doing away with mechanical models in the British tradition. In Boltzmann's case these abstruse discussions had tragic consequences. Boltzmann committed suicide in 1906, apparently convinced that the world of physics had failed to understand and appreciate his ideas.

Critics such as Mach were unhappy with the identification of thermodynamics with the atomic theory. They felt that physics should deal only with observable phenomena and avoid the unnecessary introduction of theoretical entities like atoms. The American physicist Josiah Willard Gibbs shared this concern, arguing that "one is building on an insecure foundation, who rests his work on hypotheses concerning the constitution of matter." Gibbs had gained his degree and his doctorate at Yale before spending three crucial years studying in Paris, Berlin, and Heidelberg during the 1860s. He returned to the United States to become professor of mathematical physics at Yale with a distinctly Germanic perspective on physics. Gibbs's work in thermodynamics was devoted to reducing the science to its simplest possible formulation. As he put it, "In the present state of science, it seems hardly possible to frame a dynamic theory of molecular action which shall embrace the phenomena of thermodynamics, of radiation, and of the electrical manifestations which accompany the union of atoms." Rather than trying to explain the "mysteries of nature" in this way, Gibbs declared himself "contented with the more modest aim of deducing some of the more obvious propositions relating to the statistical branch of mechanics."[35] His *Elementary Principles in Statistical Mechanics* (1902) sought to place thermodynamics on a "rational foundation" that avoided paying too much attention to elaborate mechanical models.

Maxwell's view of the implications of the atomic theory was unambiguous: "if the molecular theory of the constitution of bodies is true, all our knowledge of matter is of the statistical kind. A constituent molecule of a body has properties very different from those of the body to which it belongs . . . The smallest portion of a body which we can discern consists of a vast number of such molecules, and all that we can learn about this group of molecules is statistical information."[36] All our knowledge of the universe, in other words, was statistical. This meant that the kind of knowledge that was discoverable about the microscopic world of molecules in motion was the same kind of knowledge that was discoverable about human society—it applied to groups rather than single individuals. In fact, in a paper read to the Cambridge Apostles in 1873, "Does the progress of Physical Science tend to give any advantage to the Opinion of Necessity (or Determinism) over that of the Contingency of Events and the Freedom of the Will?," Maxwell implied that it was the statistical nature of the Universe that provided it with its sense of direction. The second law of thermodynamics did not necessarily apply to single particles. It did, however, apply to the Universe as a whole. The statistical logic that Maxwell had described as the only true logic for "practical men" really did seem to underpin that most practical of sciences, thermodynamics. Maxwell's contribution to the Apostles' debate suggests, moreover, that quite a lot hinged on what might otherwise

---

[34] Quoted in P. Harmann, *The Natural Philosophy of James Clerk Maxwell*, 139.

[35] Quoted in S. Brush, *Statistical Physics and the Atomic Theory of Matter*, 77.

[36] L. Campbell and W. Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), 439.

appear to be rather esoteric discussions about the choice of appropriate mathematical method or mechanical model. Such discussions had important ramifications for the scope and limits of human knowledge.

Conclusion

The nineteenth-century science of work developed in different ways in different contexts. Natural philosophers in England, France, the German lands, and Scotland had a range of interests and concerns. They might share what the historian and philosopher Thomas Kuhn has described as a "concern for engines," but the various ways in which that concern manifested itself was wholly contingent upon particular local cultures. The Industrial Revolution in England and Scotland had already resulted in massive and continuing changes to the cultural (and physical) landscape of the two countries. Similar processes were under way in France and the German lands by the second quarter of the century. One outcome of this was to focus philosophical and practical attention on the problem of work—its origins and the ways of maximizing its output. The ways in which this shared concern were manifested were, however, very different from country to country. In a variety of ways the science of work proved to be a good way of forging a scientific career as well. It was a way of showing how natural philosophy could itself be put to work for the national good. In this way it was to prove central to the process of finding and defining an increasingly central role for the scientist in public culture as the nineteenth century progressed.

British natural philosophers in particular were keen to emphasize the cosmological role of the science of work. They saw the second law of thermodynamics in particular as playing a central role in making the universe progressive. It was to be understood as a grand principle of dissipation that showed how the universe was gradually progressing as energy became dissipated and no longer available for conversion into useful work. It was a conception of progress that could be put to work to counter the then prevailing materialist view of progress popularized by the *Vestiges of the Natural History of Creation*. It could be used as well to expose the fallacies and pretensions of geologists and proponents of evolution by natural selection, who required that the earth have an indefinitely long history to provide the time required for their developmental mechanisms to operate. Joule's and Thomson's physics could show them that such an indefinite bank of time simply could not have existed. This is an example of the centrality of local cultural concerns to the development of the science of work throughout the century. Making common ground among physicists from different cultures and backgrounds as to what the science of work really was itself required work. It could have important implications not just for understanding the steam engine, or even understanding the Universe, but for understanding the nature of knowledge itself. As disputes between German and British pioneers and their supporters demonstrated in particular, agreement as to who the discoverers of thermodynamics were first of all required agreement as to just what the science of thermodynamics was.