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CHAPTER 4

THE CONSERVATION OF ENERGY

IN A FAMOUS PAPER, THE PHILOSOPHER THOMAS KUHN raised what seemed to him a curious question about the discovery of the conservation of energy about halfway through the nineteenth century (Kuhn 1977). Kuhn observed that this was a simultaneous discovery—within a period of about thirty years, between the mid-1820s and the mid-1850s, a number of scientists more or less independently came up with the idea of the conservation of energy. Kuhn suggested that three factors in particular played a key role in that simultaneous discovery: the concern with engines, the availability of conversion processes, and what he called the philosophy of nature. Kuhn saw these factors as central elements of European scientific thought during the period that were "able to guide receptive scientists to a significant new view of nature." There can be little doubt that the conservation of energy is one of the more crucial generalizations in the history of science—or at least of the physical sciences. It was at the very core of physics as it developed during the second half of the nineteenth century. In a slightly modified form, the principle still plays a central role in modern physics. Trying to specify the cultural circumstances that led to the development of the conservation of energy can therefore tell us a great deal about the origins of modern science.

The first question we need to ask ourselves, however, is whether a theoretical generalization like the conservation of energy is really a candidate for discovery? When we think of discoveries, we usually think of discoveries of objects or places. The discovery of America by Western Europeans comes to mind as an obvious example. Another example might be the discovery of a new planet, such as William Herschel's discovery of Uranus.

Stretching the idea, it might make sense to talk about the discovery of a theoretical entity—the discovery of the electron, say. The conservation of energy, by way of contrast, is not a place or an entity; it is a theoretical generalization. It is worth considering, at least, what it might mean to think of the conservation of energy as something that can be discovered. It does seem to commit us, for example, to the view that the conservation of energy is something that really exists in nature, rather than just in our theories about nature. This is not just a philosophical quibble since even some of the principle's "discoverers" had doubts about whether energy or its conservation were things that could be said really to exist in nature. The second question we should ask ourselves concerns the object and the simultaneity of the discovery. For the discovery to be simultaneous, all the discoverers should have discovered the same thing at about the same time. We will see, however, that our historical protagonists described their findings in a number of different ways. In particular the word "energy" was not used to describe the quantity being conserved until rather late in the day.

We shall start our survey with a look at the first two of Kuhn's elements, though we shall suggest that they can easily be regarded as different aspects of the same concern. We will commence with the French engineer and natural philosopher Sadi Carnot and his theory of heat engines, in which he sought to find a relationship between heat and work. We will suggest that this might be regarded as an aspect of a broader interest, during the period, in getting one kind of force from another—what Kuhn calls conversion processes. We will then move on to consider some of the terms used to discuss the relationships between these forces—words such as "conversion" and "correlation" as well as "conservation." In particular, we will look at the ways in which these issues were played out in the contributions of James Prescott Joule and Julius Robert Mayer. Finally, we will follow the ways in which the principle of the conservation of energy was taken up by natural philosophers in Britain and Germany, in particular, during the second half of the nineteenth century and was used as the basis for the development of a whole new way of doing physics. It should become clear that the idea of energy and its conservation had a number of uses to its discoverers. It was a way of formalizing concerns about efficiency—in both economic and physical terms—for example. It provided a way of emphasizing the authority of physics over other sciences and of demonstrating the relevance of physics to industrial progress.

Water Wheels, Steam Engines, and Philosophical Toys

During the opening decades of the nineteenth century, increasing numbers of natural philosophers across Europe were becoming increasingly interested in the relationships between the different forces or powers of nature. Specifically, they were interested in finding out how to cause any of these forces to produce any of the others. In one sense, there was nothing particularly novel about this interest. Since the beginning of the eighteenth century, natural philosophers—particularly those who described themselves as Newtonians—had been keen to investigate the properties of powers such as chemical affinity, electricity, heat, light, magnetism, and what they often called motive force. Natural philosophers such as the Scotsmen William Cullen and Joseph Black, for example, studied the properties of caloric, the substance of heat. Their researches were particularly celebrated in some circles, at least, since they were widely held to have been the inspiration behind the engineer James Watt's steam engine improvements (see chap. 17, "Science and Technology"). This was just when the burgeoning Industrial Revolution was focusing many people's attention on the question of work—and on how to exploit the forces of nature to power machinery. To some people, this seemed to be just what James Watt had done with Black and Cullen's researches. Studying the philosophical principles that underlay the operations of different kinds of machinery, as well as looking at how to turn the different powers of nature to produce motive force (or work), seemed an increasingly profitable line of inquiry (Cardwell 1971).

Some of these speculations centered on the intriguing possibility of creating perpetual motion (fig. 4.1). The German natural philosopher Hermann von Helmholtz (of whom more later in this chapter) highlighted interest in this issue as one of the driving forces that led to the conservation of energy. Many natural philosophers (as well as any number of hopeful inventors and speculators) were interested in the prospect of getting an indefinite amount of work from a finite input. To take a hypothetical example, might it not be possible to construct a water wheel that would produce enough power to pump the water falling from one level to another in order to turn it, back to the upper level? If this could be done, then the wheel should turn forever with no need for any outside source of power. It would be a machine that produced work (and therefore money) for nothing. By the end of the eighteenth century, most natural philosophers were convinced that this was simply impossible. As Helmholtz noted, however, it did focus attention on just where the work came from in such systems.

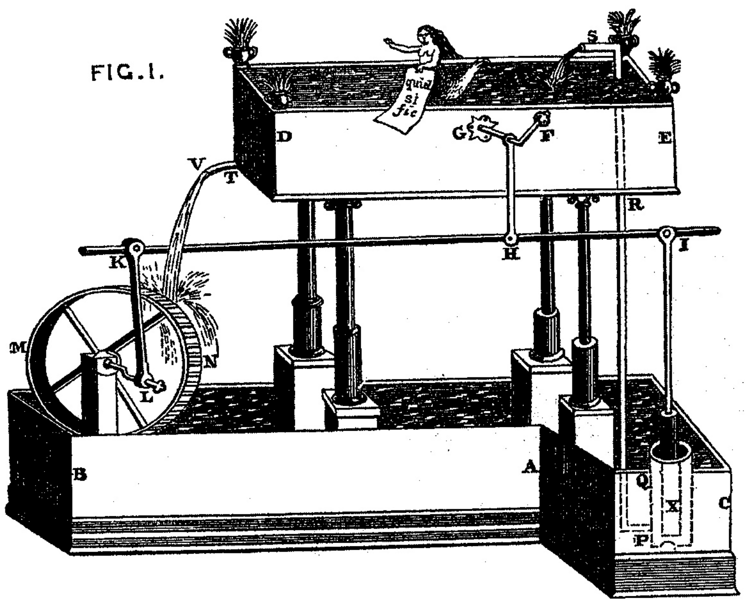

FIGURE 4.1 An example of a hypothetical perpetual motion engine. In this case, water from the upper reservoir pours down over a water wheel that, in turn, powers a pump that returns enough water to the upper reservoir to keep the motion going indefinitely. By the end of the eighteenth century, it was widely believed that engines like this were impossible.

The French engineer and revolutionary, General Lazare Carnot, for example, did some work on water wheels, showing how the amount of work produced was a function of the distance the water fell between levels in making the wheel turn.

Lazare Carnot's son, Sadi, was as interested as his father in questions about the origins of productive motive force. A committed Republican like his father as well, he wanted to find ways of putting his engineering knowledge at the service of humankind. Sadi Carnot focused his attention on the steam engine—the engine that seemed to be playing an increasingly prominent role in powering the rapid industrial expansion of France's great rival Britain. In his *Reflexions sur la puissance motrice du feu* (1824) Carnot carefully analyzed the workings of a hypothetical heat engine. Carnot regarded heat as the "immense reservoir" of nature's economy. It was the force that caused the weather, earthquakes, and volcanic eruptions. His assumption was that by understanding the operations of the actual steam engine he could gain an insight into the principles underlying the properties of the abstract heat engine as well. That, in turn, would help him to work out how to make more efficient engines. His strategy was to follow the movements of caloric—the immaterial fluid of heat—through the engine, trying to pinpoint how and where in the system motive power (or work) was produced. If he could make his hypothetical heat engine simple and general enough, he would be able to use it to "make known beforehand all the effects of heat acting in a determined manner on any body."

Carnot interpreted what happened in a steam engine in terms of the transfer of caloric from one part of the engine to another. As he saw it, that was what the steam did in the engine. The caloric developed in the furnace incorporated itself with the steam. It was then carried into the cylinder and on into the condenser. There the caloric was transferred from the steam to the cold water it found there, which was heated by the intervention of the steam as if it had been placed directly over the furnace. The steam throughout the process was only a means of transporting the caloric. 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 rather than its consumption. That was where the work came from: "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.*" Crucially, none of the caloric itself was lost in the process. As far as Carnot was concerned, caloric was conserved, just as water was conserved while producing work in the water mills that his father had analyzed. In a water mill, water did work by falling from one level to a lower level. In a heat engine, caloric did work by falling from one temperature to a lower temperature.

In 1820 the Danish natural philosopher Hans Christian Oersted made the dramatic discovery of a long-suspected link between electricity and magnetism. He found that when a magnetized needle was held near a copper wire through which a current of electricity was flowing, the needle twitched. Oersted was an exponent of *naturphilosophie*—a Romantic philosophy of nature particularly prevalent in German-speaking lands at about the beginning of the nineteenth century. Followers of *naturphilosophie,* such as the German poet Johann Wolfgang von Goethe, believed in the fundamental unity of nature. They often argued that the universe as a whole should be regarded as a single organic cosmic entity. Like a living thing, the universe was best approached and appreciated by seeing it as a connected, animated unity. Rather than being taken as separate objects of study, the various phenomena and powers of nature were to be understood as different manifestations of a single underlying and all-embracing cause. Such thinkers as Johann Wilhelm Ritter or F. W. J. Schelling often used terms like "World Soul" or "All-animal" to describe the universe. They emphasized the importance of intuition as a means of discovery and were often vociferously opposed to what they regarded as the dry sterility of analytic Newtonian natural philosophy. Coming from this perspective, Oersted was convinced that a link between electricity and magnetism must exist in nature; it was simply a matter of finding it.

A year following Oersted's discovery, the English experimenter Michael Faraday, then still a laboratory assistant at the Royal Institution, found a way to make a current-carrying wire actually rotate around a magnet. It seemed that electricity and magnetism combined could be used to produce motive force. In France, André-Marie Ampère showed that a current-carrying wire arranged as a helix acted like an ordinary magnet. He argued that magnetism was actually the result of electricity in motion and that magnets were made up of an array of electrical currents circulating around its constituent particles. It took Faraday, by now elevated to the position of Fullerian Professor of Chemistry and director of the laboratory at the Royal Institution, more than another decade to find the reverse effect. In 1832, he showed that when a bar magnet was moved inside a wire coil it produced a current of electricity. Similarly, when electricity was passed through a wire coiled around an iron ring, it produced, as it was switched on and off, a momentary current in another coil wrapped around the same ring. In the meantime, experimenters were exploiting the English instrument-maker William Sturgeon's invention of the electromagnet in 1824 to construct electromagnetic engines. With a variety of ingenious arrangements to switch arrays of electromagnets on and off consecutively, they could produce rotation. Caloric was no longer the only natural power that could be used to produce useful work.

Throughout the first few decades of the nineteenth century, experimenters were busily finding new ways of using one force to produce another. By one interpretation, Alessandro Volta's electric battery, invented in 1800, was an example—at least if one accepted Humphry Davy's explanation that it worked by transforming chemical affinity into electricity rather than its inventor's claim that the electricity was simply produced by the contact of different metals (see chap. 3, "The Chemical Revolution"). In the German state of Prussia, Thomas Johann Seebeck, inspired by Oersted's breakthrough, set out to examine the connections between electricity, magnetism, and heat. His aim was to produce magnetic phenomena by heat. Instead he found a way of producing electricity from heat. He found that if he constructed a circuit partly of copper, partly of bismuth and heated one of the junctions where the two metals joined, a current registered on a magnetized needle suspended nearby. The development of photography during the 1830s also seemed to many observers to be an example of one natural force being used to produce another. The images being produced were the result of light—one kind of force—producing a chemical reaction—the outcome of another kind of force, usually known at the time as chemical affinity. By the 1840s, more and more of these examples were building up.

In lectures at the London Institution, the Welsh natural philosopher William Robert Grove gave an experimental example of the ramifications. He demonstrated an experiment in which a photographic plate was placed in a glass-fronted box filled with water, along with a grid of silver wire connected to the plate to form a circuit along with a galvanometer and a Breuget helix. When light fell on the plate following the removal of a shutter covering the glass front, the galvanometer needles moved and the Breuget helix expanded. The light produced chemical forces on the plate, which produced electricity in the circuit, which produced magnetism in the galvanometer, which produced motion in the galvanometer needle while the electricity also produced heat in the Breuget helix, causing it to expand (more motion). Motion—motive force—was what many experimenters wanted to produce from these kinds of experiments. From the 1820s onward, they invented devices such as Barlow's Wheel, in which a copper wire rotated between the poles of a magnet when a current passed through it, and a variety of electromagnetic engines. On one level these were philosophical toys, designed to demonstrate the powers of nature to lecture audiences. At the same time, however, many natural philosophers recognized that toys such as these had the potential to provide new ways of producing motive force—of putting nature to work (Morus 1998).

The concern with engines and the interest in conversion processes were both aspects of the same preoccupation with getting work out of nature as efficiently as possible. As Helmholtz had noted, that was the concern that motivated enthusiasts for perpetual motion engines. It was what concerned Sadi Carnot in his efforts to analyze the workings of heat engines as well. He wanted to find out what the underlying principles were so that he could find ways of making engines that worked more efficiently. In just the same way, many of the researchers investigating ways of producing motion from other kinds of natural force were concerned to do so as efficiently as possible. At one level there was a theological motive to all this. It made sense that the Creator had designed the natural economy as efficiently as possible. At least as important, however, was the fact that this was a period when the question of work—and how to get as much of it as possible as cheaply as possible—was an issue of increasing concern. Making machines more efficient was an economic and moral imperative. Sadi Carnot was by no means alone in his view that working toward a better understanding nature's economy might prove to be a fruitful way of improving society's economy as well.

Conversion, Conservation, or Correlation?

By the 1830s and 1840s many natural philosophers were starting to come around to the view that these various examples of one force being used to produce another should be regarded as examples of actual transformation. That is, one force (say, electricity) was actually consumed in the process of producing another (say, heat or light). Remember that this was not a self-evident proposition—Sadi Carnot in his published work argued that caloric was not consumed in the process of producing work (though his unpublished manuscripts indicate that he later changed his mind on the issue). Even where experimenters did agree that what was going on was best understood in terms of some kind of transformation from one kind of force to another, there was a great deal of disagreement over just what kind of transformation was taking place. Natural philosophers might talk in general terms about the unity of nature—as they had done since the previous century—but there was little consensus as to how the details of that unity might be understood. Discussions about the issue are a good example of the ways in which early nineteenth-century natural philosophers crossed intellectual boundaries between areas of inquiry that we consider to be widely separated. Their arguments ranged across engineering, metaphysics, and theology as well as natural philosophy (see chap. 15, "Science and Religion").

The example of James Prescott Joule is a good one in this respect. A brewer's son from industrial Manchester, Joule's early natural philosophical enthusiasm was for electromagnetism. He made a name for himself designing and constructing electromagnetic engines during the late 1830s and formed part of the largely London-based circle of electricians around William Sturgeon (fig. 4.2). Joule was particularly concerned, however, to work out just how good his electromagnetic engines were. He applied engineering know-how and principles to the problem. He wanted to know what the duty of his engines was—this was an engineering term used to describe

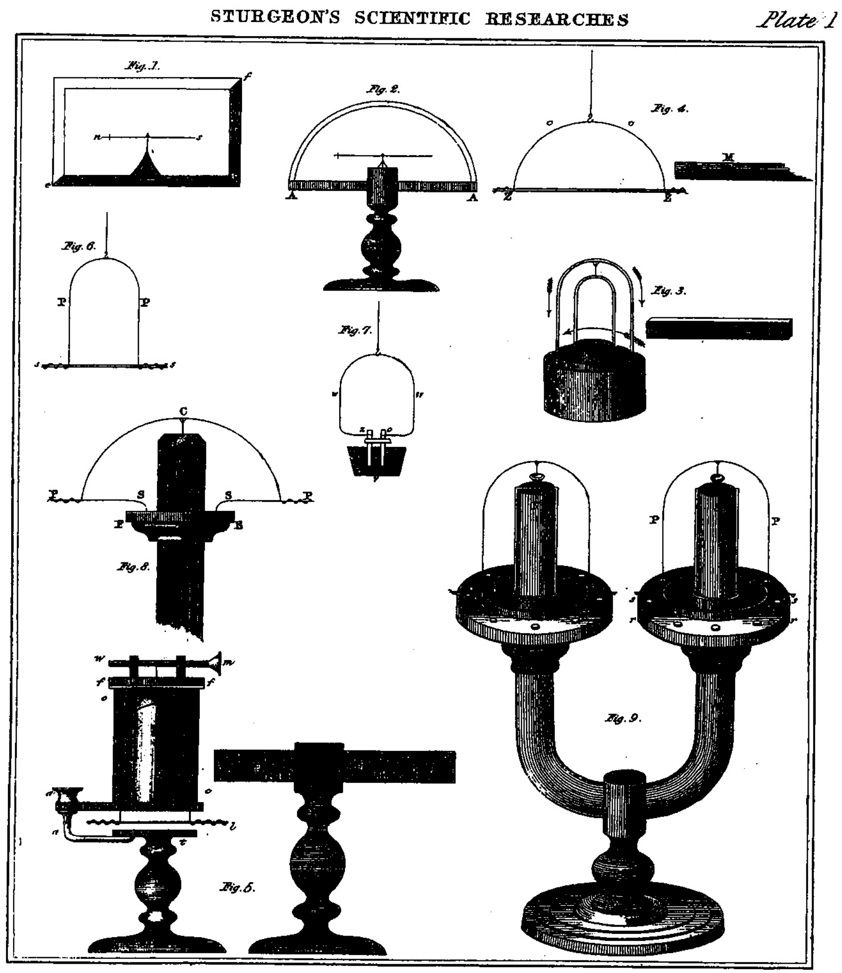

FIGURE 4.2 Instruments illustrating electromagnetism from William Sturgeon, *Scientific Researches.* Instruments such as these were meant for use in popular lectures to demonstrate the relationship of electricity and magnetism.

the efficiency of a steam engine and measured in terms of the weight in pounds that an engine could raise at a rate of one foot per second. What Joule wanted to know, quite specifically, was how much zinc was consumed in the process. Just like a steam-engine engineer, he wanted to know how much fuel was consumed to produce a given amount of work. Joule's experiments on the economic efficiency of electromagnetic engines led him

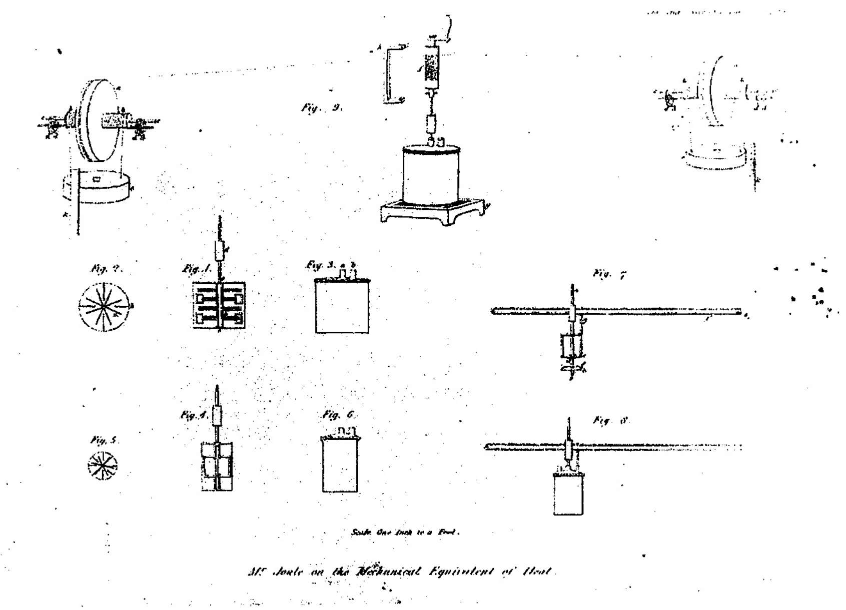

FIGURE 4.3. A diagram of James Joule's famous paddlewheel experiment demonstrating the mechanical equivalent of heat. As the weights fall, they cause the paddles inside the cylinder to rotate, heating the wafer contained in it. Joule argues that the congruent relationship between the distance the weights fell and the increase in temperature of the wafer in the cylinder demonstrated the relationship of work and heat.

to consider more general issues to do with the relationship between heat and work. By the mid-1840s, he was engaged in a series of experiments designed to work out just what that relationship was.

Joule was particularly concerned to try to find ways of quantifying the relationship between heat and work—the mechanical equivalent of heat, as he called it. In 1845 he produced the results of what is now known as his "paddle wheel experiment" (fig. 4.3). 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. As the paddle wheels rotated, the water in the container heated up. With his background in the brewing industry, Joule had access to just the kind of sophisticated thermometric apparatus and know-how that was needed to perform delicate measurements like these (Sibum 1995). Joule argued that his results showed that the motion of the weights was transformed into heat in the water. This conversion could be accurately measured as well. According to Joule, when the temperature of a pound of water was increased by one degree Fahrenheit, it had acquired a quantity of *vis viva* (as he termed motive force) equal to that acquired by a weight of 890 pounds after falling from the height of one foot. Joule called this number the mechanical equivalent of heat and argued that his experiments showed conclusively that heat was literally turned into motive force in the process of producing work.

As far as Joule was concerned, his experiments carried a theological as well as an engineering message. They provided evidence of the way God had organized creation. Joule was convinced that his experiments were proof not only that one force could be converted into another but of the conservation of force as well. He gave his most comprehensive defense of the conservation of force at a public lecture at St. Anne's Church School in Manchester in 1847. Joule argued for the reality of conservation and conversion processes in nature, that "the phenomena of nature, whether mechanical, chemical or vital, consist almost entirely in a continual conversion of attraction through space, living force and heat into one another." This was an explicitly theological argument. Joule's claim essentially was that God had created force and matter and that since God had created them, neither of them could be created or destroyed. Any apparent loss of living force, as he translated the eighteenth-century Latin mathematical term, *vis viva,* was simply the result of the conversion of one kind of force into another, just as happened in the paddle wheel experiment with the transformation of work into heat. This was a highly controversial claim and not even all those sympathetic to Joule and the general idea of the conservation of force were convinced by it. Michael Faraday, for example, insisted that Joule revise the conclusion of his paper in the Royal Society's *Philosophical Transactions* announcing his claim to reflect Faraday's own doubts on the matter.

Joule was not the first to make a grand metaphysical principle out of the results of experiments on the transformation of force. In a series of lectures at the London Institution, William Robert Grove laid out his views on what he called the correlation of physical forces. Grove argued that all the physical forces were correlated to each other—that is to say, that any one of these forces could be used to produce any of the others, interchangeably. He used the idea to mount a metaphysical assault on the philosophical idea of causality, arguing that experiment showed that no one force could be shown to cause another since they were all mutually correlative. Michael Faraday made similar claims in lectures concerning what he called the conservation of force and occasionally borrowed Grove's vocabulary of correlation. It was not at all obvious that they meant the same thing, however.

Despite his own defense of the conservation of force, Faraday disagreed with Joule's claims on the matter. Faraday argued that all Joule had shown was that the loss of a certain amount of heat always resulted in the same amount of motion. Faraday was happy with the conservation of force but was unconvinced of the conversion of force. This was largely because he shared Joule's theological commitment to the belief that anything created by God (force in this case) could not be destroyed in any natural process. In his view, turning one kind of force into another was tantamount to destroying it.

While debates like these were occupying British natural philosophers, the German doctor Julius Robert Mayer was making his own observations aboard the ship *Java*, sailing for the Dutch East Indies in 1840. In the course of his duties as ship's doctor, Mayer noticed the unusual color of the venous blood of his shipmates. It was unusually red, appearing more like arterial than venous blood, the implication being that the heat of the tropics bore some relationship to the oxygenation of the blood. It was to this observation that he attributed his interest in heat, work, and the body. Pondering the matter back on dry land, Mayer published "Remarks on the Forces of Inanimate Nature" in the *Annalen der chemie und pharmacie* in 1842. He argued for a relationship among what he called "fallforce," motion, and heat. He suggested that heat was necessarily produced during the fall of any body toward the earth's surface since such a fall was the equivalent to a slight compression in the earth's volume and it was known that compression resulted in heating. He argued that the amount of heat produced by such a fall must be proportional to the weight of the falling body and the height from which it fell.

According to Mayer, his observations aboard the *Java* had convinced him "that motion and heat are only different manifestations of one and the same force." From this he had concluded that mechanical work and heat must be capable of being converted into one another. Like Joule he was able to come up with a specific figure as well. He calculated that the fall of a given weight from a height of around 365 meters corresponded to the heating of an equal weight of water from 0° to 1° centigrade. Mayer's work had little impact at the time, though he was later to be hailed as a German pioneer of the conservation of energy. To many of his German contemporaries, Mayer's work looked obscure and out-of-touch. The silence that greeted his work, like the skepticism with which even some friendly critics regarded Joule's experiments, illustrates the difficulties surrounding the issue of force and its transformations. Experimenters disagreed as to just what their experiments showed and what their implications were. The use of different terms, such as "conservation," "conversion," and "correlation," indicated more than just semantic quibbles; they indicated real disagreements concerning the nature of the phenomena. Philosophical concerns about the nature of causality and theological issues to do with God's place in creation were at stake here as well as the more prosaic concern to build more efficient engines.

British Energy

Joule was not alone in his combination of economic, engineering, and theological concerns. Other British natural philosophers also took the view that understanding how to make machines more efficient was a way of understanding nature, too. The pursuit of efficiency, that is, the effort to minimize waste and dissipation, was both an economic and a moral imperative. For young natural philosophers such as William Thomson, born in Presbyterian Belfast and raised in the industrial city of Glasgow, natural philosophy was all about understanding nature as if it were a vast steam engine. Thomson studied natural philosophy at Glasgow University, where his father was professor of mathematics, before departing for Cambridge to study for the mathematics tripos, or final exam. Cambridge, for much of the nineteenth century, provided probably the best mathematical education available, and Thomson was a star student (Harman 1985). Thomson's natural philosophical interests, such as those of his engineer brother James, centered on work, efficiency, and the elimination of waste. He wanted to understand how nature did it so that he could apply the lessons to human endeavor. Thomson was already familiar with Carnot's theory of heat engines. He had read the mathematical version published by Emile Clapeyron while studying steam engines at the experimenter Victor Regnault's Paris laboratory after leaving Cambridge. In 1847, two years after being appointed professor of natural philosophy at Glasgow, he attended a meeting of the British Association for the Advancement of Science and heard Joule present his findings.

Thomson was impressed by Joule's experiments, but as a follower of Carnot's theory they also presented him with a problem. According to Joule, heat was lost in the production of work. According to Carnot, caloric was conserved. This was the conundrum with which Thomson would struggle for the next several years. To produce his own theory, either he was going to have to show that one of them (Carnot or Joule) was wrong or he was going to have to find a way of reconciling two apparently irreconcilable theories. (Thomson was unaware of Carnot's later and unpublished doubts concerning the material nature of heat.) Thomson shared Joule's theological conviction that nothing God created could be destroyed. He was convinced that "nothing can be lost in the operations of nature—no energy can be destroyed." This was exactly where the problem lay, however. If, as Carnot argued, work was simply the result of heat falling from one temperature level to another, what happened to the work that would have been produced if there was no engine there for it to operate on? At the same time, if, as Joule would have it, the production of work meant the absolute loss of heat, where did the heat go in cases where no useful work was being done, as in the case of straightforward heat conduction, for example?

It took Thomson until 1851 to come up with an answer. In a series of papers titled "On the Dynamical Theory of Heat," published between 1851 and 1855, he laid the framework of the new science of heat—thermodynamics. The theory rested on two central propositions. The first was a straightforward assertion of Joule's claim concerning the mutual convertibility of heat and work. This was the first law of thermodynamics—the principle of the conservation of energy. The second proposition rested on his reading of Carnot. In essence, it stated that a perfectly reversible engine—in other words, an engine that produced exactly as much work as the equivalent amount of heat lost or that would take precisely that amount of work to recover the lost heat—was the best possible kind of engine. He had abandoned his earlier commitment to Carnot's insistence that heat was conserved during the process while keeping the insistence that work could only take place when there was a transfer of heat from a higher to a lower temperature. In any process of heat transfer that did not fulfill Carnot's criterion of perfect reversibility—in other words in any real engine—Thomson concluded that there was "an absolute loss of mechanical energy available to man." This was the second law of thermodynamics.

Over the next few years Thomson worked with like-minded allies such as Peter Guthrie Tait and W. J. Macquorn Rankine to make his new dynamic theory of heat into a whole new way of doing natural philosophy, with the new concept of energy, not force, at its very core. Along with P. G. Tait (they jokingly referred to themselves as T & T′), Thomson wrote the monumental *Treatise on Natural Philosophy* to demonstrate the possibilities of the new science of energetics. It was an ambitious project, with the two men self-consciously regarding themselves as stepping into Newton's shoes and writing the new *Principia.* Thomson was the first to start using the term "energy" in a new and precise mathematical sense. Its previous usage had been as a loosely defined synonym for force or power. It now meant simply that mathematical entity which was quantitatively conserved in force transformations. Many of Thomson's critics were unhappy with this new emphasis on energy. The veteran English natural philosopher John Herschel (son of William Herschel, discoverer of Uranus) argued that energy did not really exist, that it was a mere mathematical fiction. He argued for the retention of force as the key concept in natural philosophy since force at least had a tangible and intuitively obvious meaning. In Herschel's view, the introduction of energy deprived natural philosophy of physical meaning.

Thomson and his cohorts were confident that energy and its ramifications went much further than thermodynamics. Energy and its components would serve to unify natural philosophy. Electricity, light, and magnetism could all be understood as energy. The conservation of energy had a role to play in chemistry as well, explaining how chemical reactions took place. It even had a role to play in geology and biology. Thomson was a fervent opponent of new Darwinian ideas about the origins of species, for example (see chap. 5, "The Age of the Earth"). He used the new science of energy to show just how wrong those theories were, demonstrating how thermodynamics proved that neither the earth nor the sun could possibly be old enough to sustain the long and slow geological and evolutionary changes needed by the latest theories. What Thomson was doing in these debates—and what he and Tait were doing in their *Treatise*—was largely about demonstrating the superiority of their kind of natural philosophy. They were showing how energy could be used to solve other disciplines' problems. Energetics was also an example of the usefulness of natural philosophy. It provided a recipe for building better steam engines. It also captured and reflected the industrial culture of Victorian Britain, providing a model in nature for a society that wanted to maximize efficiency and minimize waste (Wise 1989–90).

One enthusiast for the new science of energy was James Clerk Maxwell. He placed energy at the heart of the new theories of electromagnetism that he started developing from the 1850s onward. Having taken William Thomson's advice to read Michael Faraday's *Experimental Researches in Electricity and Magnetism* carefully, Maxwell produced his first paper, "On Faraday's Lines of Force," in 1855. There and in subsequent contributions, he provided a mathematical elaboration of Faraday's explanations of electrical and magnetic phenomena in terms of the distribution of hypothetical lines of force through space. Conscious of critics' complaints about the intangibility of energy, Maxwell laid out a complex mechanical model of molecular vortices and idle wheels to represent his theory. His mathematical theory described a real existing medium—the ether—where energy was stored and transformed from one sort to another (fig. 4.4). Maxwell's electro-

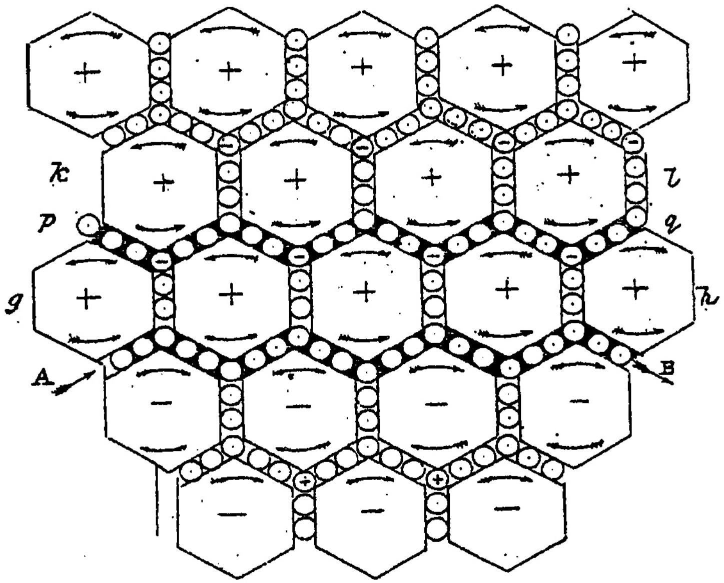

FIGURE 4.4 James Clerk Maxwell's model of a possible mechanical structure for the ether.

magnetic theorizing culminated with the *Treatise on Electricity and Magnetism* of 1873, published just two years after Maxwell had been appointed as first Cavendish Professor of Physics at the University of Cambridge. Just like Thomson and Tait, he was trying to build the foundations of a comprehensive new science based on the concept of energy. He was adamant that electromagnetic energy and the ether were not hypothetical entities. They were as real as anything else in the universe.

The ether rapidly became the embodiment of energy for nineteenth-century British physicists. As far as many of them were concerned, the physics of energy was practically synonymous with the physics of the ether. Physicists, including Oliver Heaviside, Oliver Lodge, and George FitzGerald, took the main business of physics to be working out the physical and mathematical properties of the ether. In 1885, Fitzgerald, for example, developed what he described as a "vortex sponge" model of the ether, with the ether visualized as a three-dimensional network of spongy, compressible vortices filling all space. The aim was to be able to rewrite Maxwell's electromagnetic equations in purely mechanical terms as descriptions of a real mechanical system. Electromagnetic waves, for example, would be understood quite literally as mechanical vibrations in a physical medium. If Thomson's thermodynamics was the physics of the steam engine, Maxwellian electrodynamics was the physics of the Victorian telegraph system. The electric telegraph had been one of the major achievements of Victorian engineering, and Maxwellian physicists were keen to demonstrate their science's capacity to explain its operations. They regarded the discovery by Heinrich Hertz—one of Hermann von Helmholtz's students—of electromagnetic waves in 1888 as a massive vindication of Maxwellian theory and as a victory over practical electrical engineers such as William Preece, head of the post office's telegraph department, who denied the applicability of Maxwellian physics to practical engineering issues.

Men such as Joule, Thomson, and Maxwell were particularly keen to make the science of energy practical and tangible. Not everyone agreed with this perception of what physics should be about. The French physicist Pierre Duhem was scathing about the way the physics of energy seemed to be the physics of the factory, too. He did not understand the British obsession (as he saw it) with making sure that the concept of energy was firmly anchored in reality. He regarded physics as a far more abstract business and had no problem with the prospect of theoretical entities that had no physical counterpart. British physicists, aware maybe of the criticisms aimed at them by opponents such as John Herschel, wanted to make sure that energy was recognized as a real entity, however. The physicist Oliver Lodge went so far as to say that the existence of the ether was as firmly established as was the existence of matter. This was a feature of their concern with the practicality of their science too. Most British physicists would not have been as insulted as Duhem would have wanted them to be by his comment that their physics was tainted by the factory floor. They were proud of the fact that their physics was above all practical.

The German Science

In the German lands during the second quarter of the nineteenth century, there were also moves by a new generation of natural philosophers to reform the practice and the key concepts of their science. In particular, many of this new generation were keen to disassociate themselves from what they perceived as the metaphysical excesses of the previous generation's *naturphilosophie.* They castigated their predecessors' science for being too speculative, obsessed with the unity of nature and treating the universe almost as if it were a living thing. Rising practitioners such as Emile du Bois Raymond, Carl Ludwig, and Hermann von Helmholtz embraced materialism and rationalism instead. Helmholtz studied medicine as a student at the University of Berlin during the early 1840s. Over the next few years he served as a staff surgeon in the Prussian army while carrying out experiments on the role of heat in muscle physiology and making a name for himself in physiological circles. In 1849, with the help of his former teacher, the physiologist Johannes Müller, Helmholtz got a job as professor of physiology at the University of Königsberg. Where their predecessors had wanted to show that the universe could be treated like a living organism, the new generation of physiologists of whom Helmholtz was part wanted to show that living organisms could be treated like machines (fig. 4.5).

In 1847, two years before he took up his professorship, Helmholtz published a little pamphlet called *Über die Erhaltung der Kraft* (On the conservation of force). Helmholtz based his theory of conservation on the denial of perpetual motion. If the amount of work done by a system in changing from one state to another were not the same as the amount of work that would be needed to change it back, then perpetual motion would be possible. He then proceeded to show how his theory applied in mechanical systems—those involving motion under the influence of gravity, the motion of elastic bodies, wave motion, and so on. In dealing with mechanical systems in which it had been supposed previously that an absolute loss of force took place, such as those involving friction or the collision of inelastic bodies, Helmholtz raised the possibility of the mechanical equivalence of heat, citing some of Joule's early experiments as evidence. He argued that heat could not be a species of matter, as the caloric theory suggested, since experimental evidence suggested that there were ways (like mechanical friction or magneto-electricity) of producing indefinite amounts of heat in a system. If heat were a kind of matter, then it would seem, according to Helmholtz, that it could be produced out of nothing.

Helmholtz applied the same kind of mechanical principles to the phenomena of electricity and magnetism. He went through a thoroughgoing analysis of motion under the influence of electrical and magnetic forces. He picked up on Joule's experiments on the relationship between electricity and heat and provided detailed consideration of the action of different kinds of batteries, such as Daniell and Grove cells. Helmholtz concluded his essay with an examination of the conservation of force in organic bodies. He was, after all, a physiologist—and one who was committed to showing that physiology could be studied on materialist principles. Helmholtz's earlier physiological work had been aimed at showing how the heat of animal bodies and their muscular action could be traced to the oxidation of

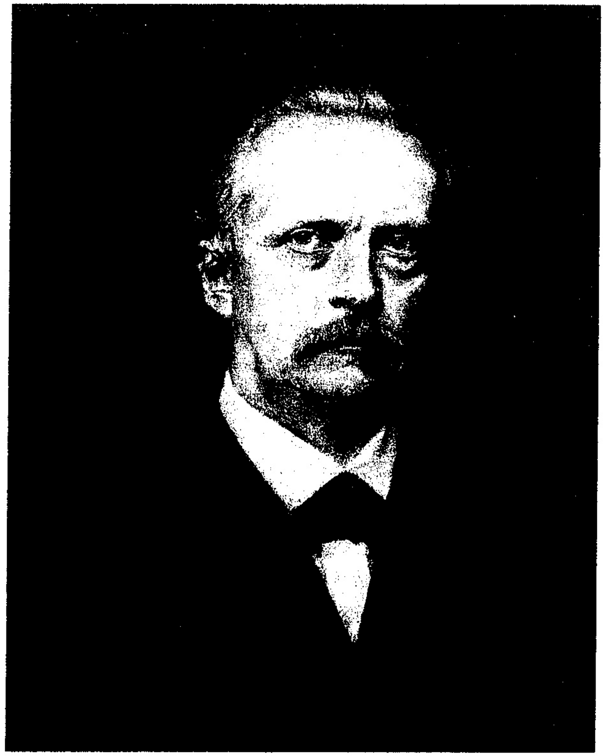

FIGURE 4.5 The German physicist and pioneer of the conservation of energy, Hermann von Helmholtz (The Wellcome Trust, London). By the time of his death in 1894, Helmholtz was widely regarded as the leading figure in German science.

food—their fuel. His research was following in the footsteps of the German chemist Justus von Liebig, who had pioneered research into the connections between the chemistry of nutrition and vitality. He argued that experiments by physiologists comparing the amount of heat produced by the combustion and transformation of the substances taken in as nutrition equaled the amount of heat given off by living things. In other words, there was no missing vital force to be accounted for. Organic bodies obeyed the conservation of force like every other natural system.

Helmholtz published his essay in pamphlet form since it had been rejected for publication in the prestigious *Annalen der Physik*. The editor, the physicist Johann Christian Poggendorff, turned it down on the grounds that it was too speculative and did not contain enough new experimental material. Helmholtz was, moreover, a physiologist not a physicist by both training and profession. His position at Königsberg brought him into contact with mathematically trained physicists such as Carl Neumann, however. Gradually, physicists started paying attention to Helmholtz's speculations concerning the conservation of force, and Helmholtz acquired expertise in experimental physics and mathematics. Throughout the 1850s, his researches increasingly bridged the gap between physiology and physics, many of them like his experiments with Neumann on the propagation of electricity through nerves being aimed at working out the physical properties of physiological systems. By the 1860s he was increasingly recognized as a physicist, and he ended his career as director of the prestigious Berlin Physikalisch-Technische Reichsanstalt. He produced a new generation of German physicists, including Heinrich Hertz, who would apply and extend Helmholtz's own theoretical researches on the conservation of energy into new areas. One of the first physicists to take Helmholtz's work seriously was, however, Rudolf Clausius, a young schoolteacher recently graduated, like Helmholtz himself, from the University of Berlin.

Clausius had written his doctoral dissertation under the supervision of the physicist Gustav Magnus on the light-dispersing and luminous effects of the atmosphere, looking in particular at the ways in which tiny particles in the atmosphere reflected light. He moved on 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 the French experimenter Regnault's work and of Clapeyron's interpretation of Carnot's theory. In 1850 he published "On the Moving Force of Heat, and the Laws regarding the Nature of Heat Which Are Deducible Therefrom" in Poggendorff's prestigious *Annalen der Physik.* His argument was based on his reading of a paper on Carnot's theory by William Thomson in 1849. He argued that it was possible 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. All that was needed was to drop Carnot's assumption that heat was conserved during the production of work. Clausius suggestion was that the production of work by heat required both the flow of heat from one temperature level to another and the conversion of a certain proportion of the heat into work. Both Carnot and Joule were therefore correct, so long as Carnot's claims concerning the conservation of caloric were relegated to the status of a superfluous subsidiary statement. This was much the conclusion at which Thomson would arrive in his 1851 paper "On the Dynamical Theory of Heat."

Clausius continued to work on his theories of heat throughout the 1850s and beyond. In 1853 he dealt with Helmholtz's essay, praising it for its "many beautiful ideas" but criticizing it for its mathematical inexactitude. Clausius's main concern was to try to find connections between the dynamic theory of heat and the work on gases in motion that had originally drawn his attention to the issue. 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. In his view, heat was simply the outcome of the motion of these particles. Hot gases were made up of fast-moving particles while colder gases were made up of slower particles. Since the molecules in hot bodies were moving faster, they tended to be further apart from each other, and Clausius argued that heat could therefore be expressed in terms of this distance. In 1865, Clausius introduced a new concept—entropy—into the dynamic theory of heat, so that he could rewrite the second law of thermodynamics as the assertion that the entropy of the universe tends to a maximum. The Austrian physicist Ludwig Boltzmann later argued that this meant that the second law of thermodynamics was statistical in nature and that entropy should be understood as a statistical term defining the relative order or disorder of the system. This was a big step, implying as it did that the law of cause and effect only had a statistical, rather than absolute validity at molecular levels.

Thermodynamics and energetics as they developed in German hands were very different affairs from the British version, particularly in the case of Clausius's work. The science that Clausius produced was self-consciously abstract and rationalist. It was avowedly and deliberately the antithesis of the previous generation's wildly metaphysical *naturphilosophie.* Like Helmholtz, in papers produced during the 1850s and 1860s he expanded his work on heat to consider electrical phenomena as well. The basis for his comparison of electricity with heat was, however, explicitly mathematical rather than experimental. In many ways, the kind of research that Clausius and his students pursued was a 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. By the 1860s, it was rapidly becoming clear that however much it might appear to the casual observer as having much in common with it, this German science was the direct antithesis of the kind of practical natural philosophy that William Thomson and other similar-minded British physicists practiced. As Clausius's researches developed during the 1860s, James Clerk Maxwell complained that they bore less and less reference to material, physical reality. As far as he was concerned, even the most abstract mathematical concept had to have a measurable component if it was to be a part of a physical theory. Theoreticians such as Clausius had no such scruples. Unlike the British, German physicists had little interest in working out the mechanical structure of the ether. What mattered to them was the mathematics.

Conclusions

In many respects, Thomas Kuhn was clearly right. There was a simultaneous discovery of the conservation of energy during the second quarter of the nineteenth century. The personages highlighted here as well as several others came up with versions of what now look like the conservation of energy. Kuhn names twelve of them (while somehow missing Thomson and Clausius), and it would not be too difficult to come up with others. That what was being discovered by these various protagonists was in any sense the same thing—or indeed that anything was being discovered at all—is, however, the product of retrospection. It is only with hindsight that the various experimental claims and theoretical generalizations discussed here seem to add up to the principle we now recognize as the conservation of energy. When they were originally made, they might just as easily seem to pertain to whole different sets of concerns and issues. What we now regard as a straightforward piece of empirical science was regarded by Joule or Thomson—or Michael Faraday, for that matter—as a fundamentally theological issue. It was not simply over matters of detail that many of the simultaneous discoverers disagreed with each other about just what had been found. They disagreed about the fundamental meaning of what had been discovered and how it fit into the general scheme of natural philosophy.

None of this basic disagreement prevented vociferous priority disputes later in the century when it had been decided that a fundamental discovery had indeed been made. A number of figures laid claim to the discovery of the conservation of energy during the second half of the nineteenth century. William Robert Grove, for example, proclaimed his 1846 publication *On the Correlation of Physical Forces* as the key text, a claim that P. G. Tait dismissed as "humbug." Many British natural philosophers did, however, continue to use the term "correlation of forces" interchangeably with "conservation of energy" until at least the 1880s. In Britain, most commentators pointed to James Prescott's Joule's experiments on the mechanical equivalent of heat as the crucial discovery. In Germany, likewise, historians of the new doctrine of energy pointed to Robert Mayer as its originator. There were dissenters—the Anglo-Irish natural philosopher John Tyndall, a vociferous opponent of Thomson's and Tait's form of physics, agreed with the Germans that Mayer rather than Joule was the real discoverer. The American physicist Josiah Willard Gibbs gave the laurels to Clausius, while P. G. Tait claimed that Clausius's excessive mathematical abstraction debarred him from consideration. The British and the Germans were particularly vociferous in their claims and counterclaims. Laying claim to having originated nineteenth-century physics' key theory was a matter of national pride.

The principle of the conservation of energy did, regardless, play a key role in the nineteenth century, institutionally as much as intellectually. On the one hand, it provided a new and powerful theoretical tool for understanding nature. On the other, it provided an equally powerful resource for the institutional reorganization of natural philosophy. If we are looking for origin points, it might not be unreasonable to argue that the conservation of energy marks the end of natural philosophy and the beginning of physics as we know it. The principle of the conservation of energy provided a focus for the emergence of physics as a discipline. It gave physicists a common set of experimental and theoretical practices and theories—though as we have seen it took some time for this common perspective to appear. Historians have argued that it was during the nineteenth century that science became a profession in the modern sense. In that case, the conservation of energy certainly provided common ground for the forging of a professional identity for physicists. It provided a way of demonstrating the intellectual and practical power of the new discipline. With its connections to steam engines and telegraphs, it signaled the important role that physics could play in industrial society.

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