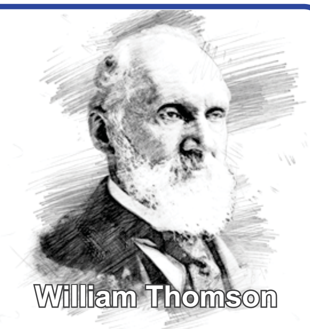
Conceptualizing Energy

Conservation of Mechanical Energy and the Introduction of Potential Energy


William Thomson

Most students who have taken high school chemistry or physics know the First Law of Thermodynamics: "Energy can neither be created nor destroyed." But at the beginning of the nineteenth century, physicists had not yet formulated this fundamental law of nature. Moreover, at this time the term "energy" did not have a precise scientific definition, and most physicists thought matter and force were the only concepts needed to understand the natural world.

The idea that mechanical energy is conserved and the introduction of potential energy transformed the study of energy into one of the most important and exciting areas of nineteenth-century physics. But assigning credit for developing these principles is difficult. The great Scottish physicist William Thomson (1824-1907) is generally given credit for stating the first law, but to do so he drew on the work of physicists and engineers from France, Germany, and Great Britain. Sadi Carnot (1796-1832), Émile Clapeyron (1799-1864), James Prescott Joule (1818-1889), Rudolf Clausius (1822-1888), and William Rankine (1820-1872) all made significant contributions to the new discipline of energy physics.

Many people envision scientists working alone. However, science is rarely a solitary activity. Scientists often communicate with one another, collaborate on papers, meet in teams, and attend conferences. As you read this story, note the collaborative and competitive nature of scientific work.

France and Germany: Carnot, Clapeyron, Mayer, and Helmholtz

In the eighteenth and early nineteenth century, few physicists or engineers used the word "energy" in their work. Instead, physicists more often discussed something called *vis viva,* Latin for "living force." The great German philosopher and physicist Gottfried Wilhelm von Leibniz (1646-1716) defined a body's *vis viva* as its mass times the square of its velocity (mv^2). Leibniz, a deeply religious man, argued that God had established the universe's total amount of *vis viva* at the time of its creation, and thus the total amount of *vis viva* in the universe could not change. By the early nineteenth century, many French engineers had realized that the total work a moving body could perform was equal to half of its *vis viva.* These engineers redefined "work" as $\frac{1}{2}mv^2$.

One of the most important French engineers of the early nineteenth century was a man named Sadi Carnot (1796-1832). As a young man, Carnot watched his home country lose the Napoleonic Wars to England. He was convinced that England's military superiority was due entirely to its industrial superiority, in particular its steam engines. Carnot became interested in how France could improve its own steam engines, and began thinking about the physics behind the way engines worked.

Science and technology are not the same, but they do significantly impact one another. Science seeks to understand the natural world, and the knowledge it creates is often essential for technological development. Technology, in turn, assists in science research. At times, scientific research is driven solely by scientists' desire to understand the natural world with no thought of its application. This is referred to basic or pure science. At other times, as with Carnot's work, science is driven by a perceived societal problem. This type of research is referred to as applied research. Basic science, applied science, and technology all play a crucial role in understanding nature and in technological advancement.

In 1824, Carnot published the book, *Reflections on the Motive Power of Heat.* Like most physicists and engineers at the time, Carnot believed that heat was a fluid called "caloric." He thought that caloric was able to do work when it flowed from an area of high temperature to an area of low temperature. He wrote:

> 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 re-establishment of equilibrium—an equilibrium considered as destroyed by any cause whatever, by chemical action such as combustion, or by any other.

Initially, Carnot's book drew little attention, but in 1834, two years after his death, a mathematician and physicist named Émile Clapeyron (1799-1864) published an essay called "On the motive power of heat." Clapeyron's paper gave mathematical form to, and prompted physicists to consider, Carnot's ideas. William Thomson, for example, carefully read Clapeyron's paper and was heavily influenced by Carnot's thinking.

Others were also thinking about the relationship between heat, work, and the conservation of *vis viva.* In 1841, the German physician Julius Robert von Mayer (1814-1878) returned to Germany from the Dutch East Indies. Mayer had served as the ship's doctor during the voyage. He had observed the physical condition of the crew and noticed differences in their body chemistry in warm versus cold climates. He came to the conclusion that the human body did not have to work as hard to produce body heat when humans were in warm climates. In 1842, Mayer published a paper called "On the Forces of Inorganic Nature," which argued that the work needed to raise the temperature of 1 kilogram of water by 1^{0}C was the same as the amount of work a 1-kilogram weight would perform if dropped from a height of 365 meters. But Mayer's argument was entirely based around theoretical calculations. German physicists, who preferred to base their science on experimental evidence, largely ignored the paper.

1. Not all science is experimental. Galileo, Einstein, Newton and other scientists put forward mathematically derived ideas, leaving to others the confirmation of their theoretical frameworks. How does this illustrate that no single scientific method exists?

Meanwhile, the German professor Hermann von Helmholtz (1821-1894) was thinking about the conservation of *vis viva,* and he set out to determine if force was also conserved in nature. In 1847, Helmholtz published an essay, "On the Conservation of Force," which argued that many different sources of force existed – chemical reactions, electricity, heat, and mechanics – but that the total force in any chemical or physical process had to be conserved. Helmholtz, who had a medical background, was particularly interested in how the human body was able to do work through muscle contraction. He concluded that a chemical reaction took place during muscle contraction, and that the force from that chemical reaction was responsible for moving the muscles.

Although Meyer and Helmholtz would later be identified as two men who early on recognized a relationship between heat and work and the principle of the conservation of force, at the time few other men of science were familiar with their papers. The work that would most influence thinking regarding this relationship was conducted in Great Britain, near the industrial city of Manchester, by a young brewer's son named James Prescott Joule.

2. Carnot, Mayer, and Helmholtz worked in different fields. However, they each assumed that heat, work, and conservation of *vis viva* were not unique to their respective disciplines, but rather that they cohere or join together. Scientists are often skeptical of ideas that do not cohere together. What rational reasons exist for the expectation that science ideas should cohere?

James Prescott Joule and his experiments

James Prescott Joule was born Christmas Eve in 1818. He was the son of a wealthy brewer in a town called Salford, near the industrial city of Manchester. James suffered from delicate health as a child, and he and his brother Benjamin were both educated by private tutors. In 1834, their father arranged for James and Benjamin to study with John Dalton, a renowned natural philosopher and the President of the Manchester Literary and Philosophical Society. Although Dalton suffered a stroke two years after he began teaching the Joule brothers, he was an important influence on James' views about natural philosophy. Dalton taught Joule that the universe was governed by natural laws, and that these laws could be discovered through careful experiments and precise measurements.

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The word "discover" can wrongly be interpreted as merely finding what was previously unknown. As you read this story, think about how scientists are drawing from existing knowledge, their work with others, and creativity to develop ideas to account for data. As opposed to merely finding or discovering ideas, scientists develop ideas via an iterative process that over time better make sense of the natural world.

In the nineteenth century, most natural philosophers (today referred to as scientists) needed other jobs to earn an income. Few could afford to pursue research full-time. But Joule's family wealth gave him the opportunity to devote himself entirely to chemical and physical research. Like many other inventors, industrialists, and natural scientists in the 1830s, Joule was extremely interested in electric motors. The steam engines that drove industry and transportation in the early nineteenth century were large, dirty, and noisy; many people in Britain hoped the new electric motors would replace them.

The word "scholar" comes from the Latin word "scholee" which means "leisure time." Today we hardly think of conducting scholarly work as "leisure." However, long ago, science and other forms of scholarship were associated with leisure time.

In the late 1830s Joule began experimenting with electric circuits to see if he could work out the best design for an electric motor. By 1840, at the age of twenty-one, Joule had put forward the idea that the heat in a circuit is proportional to the resistance and the square of the current (i^2r). Joule also noticed that when electric motors gave off more heat, they were unable to do as much work. He began to think that heat and work were related, and that a precise mathematical law might express the amount of heat a certain amount of work would generate. Joule's ideas were strikingly similar to Mayer's, but Joule did not know about the German physician's paper.

James Prescott Joule

Joule spent the early 1840s designing and carrying out a series of experiments to measure this exchange rate between heat and work. Most famously, in 1845 Joule constructed a paddle wheel that fit inside a cylindrical vessel. He filled the vessel with a precisely measured quantity of water and inserted a thermometer into the water. He then attached the paddle wheel to a weight, allowed the weight to fall from a measured distance (turning the paddle wheel as it fell), and recorded the change in the temperature of the water as the paddle wheel turned. From this, he was able to calculate the amount of heat generated by the work of the paddle wheel, and determined that the exchange rate for work and heat was 772 foot pounds per British Thermal Unit.

By the mid-1840s, Joule had published and presented several papers on the exchange rate of heat and work. However, many natural philosophers were unconvinced that the two were related, and few thought Joule's work was of much importance. In 1847, however, Joule had the opportunity to read a paper about his work at the Oxford meeting of the British Association for the Advancement of Science. Years later, Joule recalled the meeting and wrote,

> [T]he communication would have passed without comment if a young man had not risen in the section, and by his intelligent observations created a lively interest in the new theory. The young man was William Thomson.

William Thomson and the conservation of energy

William Thomson was born in 1824 in Belfast, Ireland, but spent most of his childhood in Glasgow after his father accepted a professorship of mathematics at Glasgow College. At the age of seventeen, Thomson began studying mathematics at the University of Cambridge. In 1846, at the age of twenty-two, Thomson was elected to the Glasgow College chair of natural philosophy. Like Joule, Thomson was interested in engines and motors. While William was at Cambridge he and his brother James, who was an engineer, exchanged long letters about work, power, and heat in engines. The brothers were particularly interested in the Carnot-Clapeyron work. Carnot's engine model and Clapeyron's equations describing Carnot's engine seemed to provide the best description of the way an engine worked, but Thomson was puzzled why engines did not perform as much work as Clapeyron's calculations said they should. When Thomson heard Joule's paper at Oxford in 1847, he realized that Joule's experiments might resolve his problem – the engines were losing work because some of that work was being converted into heat.

Note how Thomson is bothered by the discrepancy between theory and observation, yet he does not reject the theory. Note also how theory provides a framework for conducting further research and in noting a possible solution. In everyday language, theory is interpreted as a guess, but in science, theories are explanations that also provide a framework for research.

After hearing Joule's paper, Thomson built his own cylinder and paddle wheel and began working to better understand the relationship between heat and work. Thomson accepted Joule's conclusion that work could produce heat. But in his paper, Joule had also argued that heat could, in principle, also be converted back to work. Thomson was not convinced of this second point. Following Carnot and Clapeyron, Thomson thought mechanical work was created when heat flowed from an area of higher temperature to an area of lower temperature – similar to water flowing from a spout and turning a paddle wheel as it fell. Joule's idea that heat could be transformed into work appeared not to agree with the Carnot-Clapeyron model, especially since Carnot had said that no heat was lost in this process.

James Prescott Joule, adapted from Henry Roscoe By Henry Roscoe, Public Domain, https://commons.wikimedia.org/w/index.php?curid=3119134

Thomson also saw a problem with Carnot's theory. He knew of many situations in nature where heat flowed from an area of high temperature to an area of low temperature without producing work – for example, the straightforward conduction of heat through a solid did not appear to produce any work. Did that mean the work that the flow of heat could have done had been destroyed?

The idea that work could be destroyed was unacceptable to Thomson for both scientific and religious reasons. Like most natural philosophers, Thomson believed that the universe was balanced; it was not enough to say that work was "lost," you had to account for where it went. Thomson was also a devout Presbyterian, and he believed that God had created energy and only God could destroy it. "Nothing can be lost in the operations of nature—no energy can be destroyed," Thomson wrote in 1849. "What effect then is produced in place of the mechanical effect which is lost?"

3. Scientists are human beings and thus are influenced by personal and societal beliefs. Note how Leibniz (see first portion of this story) and Thomson were influenced by their religious beliefs, but do not invoke God in their scientific explanations. How does this illustrate that while science and religion sometimes clash with one another, complex interaction rather than warfare better accounts for their interplay?

Rudolf Clausius and William Macquorn Rankine

Thomson, assisted by the work of a German scientist, Rudolf Clausius (1822-1888), and a fellow Scotsman, William Macquorn Rankine (1820–1872), sought to solve the apparent contradiction between Joule and Carnot. Rankine was the son of an Edinburgh engineer, and his father encouraged his interest in technology and the natural world. William took a few courses at the University of Edinburgh and considered attending Cambridge, but instead decided to start a professional career as a railroad engineer. Rankine maintained his interest in natural philosophy, and in 1849 he became a member of the Royal Society of Edinburgh.

In October 1849, Rankine contacted his former professor James David Forbes about a paper he was writing on a new theory of heat. Rankine had developed a theory that heat was not a fluid (as Carnot and Clapeyron had thought), but the result of the vibration of something called "molecular vortices" within individual molecules. He argued that heat could produce mechanical action when the movement of the "molecular vortices" was converted into the movement of mechanical parts. In 1850, Rankine presented his theory to the Royal Society of Edinburgh, and sent a copy to William Thomson.

Thomson was intrigued by Rankine's idea of heat as a motion. When he encountered Clausius' work, he became convinced that this new theory of heat could help him reconcile Carnot and Joule. Clausius was a young Prussian physicist teaching and studying at Berlin University. He knew about Thomson's work and was very interested in the physics of heat. After reading Thomson's paper on the conflict between Joule's theory and Carnot's, Clausius began to think about how to solve Thomson's problem.

In 1850, Clausius published a paper, "On the Moving Force of Heat, and the Laws Regarding the Nature of Heat which are Deducible Therefrom." Clausius' paper proposed a theory very similar to Rankine's: that heat was not a fluid, but a measure of the motion of particles. In other words, hot air was not hot because it contained a fluid called "caloric," but because its particles were moving more rapidly than the particles in cold air. Clausius argued that Carnot was correct in that work could be generated by heat flowing from an area of high temperature to an area of low temperature, but he was wrong about an engine losing no heat when work was performed. Clausius backed Joule's conclusion that work and heat were mutually convertible:

> In all cases where work is produced by heat, a quantity of heat proportional to the work done is expended; and inversely, by the expenditure of a like quantity of work, the same amount of heat may be produced.

4. Well-established science knowledge is very durable and trustworthy. However, regardless of how durable well-established science ideas may be, all science knowledge is still potentially open to revision or even rejection by the scientific community. How is the possibility of revisiting and revising previously established ideas a strength of science?

The new science of energy

Clausius' paper and Rankine's work convinced Thomson that both Joule and Carnot were right. In "On the Dynamical Theory of Heat," a paper he published in 1851, Thomson agreed with Clausius and Rankine that heat was not a fluid, but the motion of particles in a body. When heat was conducted through a solid body, no energy was lost. Instead, the energy was converted into the motion of particles in the solid. Therefore, work could be converted into heat, and heat could be converted into work.

So far, "On the Dynamical Theory of Heat" may not appear particularly groundbreaking – after all, Rankine and Clausius had come to the same conclusions in their papers. But Thomson's paper was important for introducing the term “energy” into nineteenth-century physics. The word “energy” had been used in scientific texts before to describe the power released during a chemical reaction or the burning of coal, but Thomson was the first to say that both heat and work were forms of energy. In any chemical or physical process, energy could be converted from one form to another, but energy could never be created or destroyed. The First Law of Thermodynamics reflects this conclusion.

Rankine was excited by Thomson's work, and he began promoting the concept of “energy” as the key to modern engineering and physics. In 1853, Rankine published an important paper, “On the General Law of the Transformation of Energy,” which defined “energy” as:

> every affection [state] of substances which constitutes or is commensurable with a power of producing change in opposition to resistance, and includes ordinary motion and mechanical power, chemical action, heat, light, electricity, magnetism, and all other powers, known or unknown, which are convertible or commensurable with these.

Rankine's paper also contained another important development. Rankine defined two different types of energy: actual and potential. “Actual” energy (what we now call kinetic energy) was defined as the energy possessed by a body in motion – i.e., $\frac{1}{2}mv^2$. “Potential” energy was energy stored in a physical system that could be used to do work. For example, a heavy weight with mass m held at height h did not have any “actual” energy because it was not in motion, but it did have a potential energy of mgh. This distinction between actual and potential energy helped Rankine and the other energy physicists show that the law of conservation of energy was still upheld in cases where it might seem that new energy was being created. For example, under Rankine's new terminology, the falling weight Joule used to turn his paddle wheel back in 1845 was converting its potential energy into actual energy; it was not turning the paddle wheel by creating new energy.

Today, the law of conservation of energy is widely recognized as one of the fundamental underlying principles of the universe, and Rankine's definition of potential energy is in every physics textbook. Although William Thomson and his fellow Britons Joule and Rankine are the names most often associated with the development of the principle of conservation of energy, this scientific concept had a long history stretching back to the eighteenth century. Its full development was due not just to these three men but also to physicists, doctors, and engineers from across Europe. Without the work of the obscure French engineers Carnot and Clapeyron and the young German professor Clausius, Thomson and the others likely would have had a far more difficult time formulating their new science of energy.

Perhaps even more interestingly, two papers that might have been extremely useful – Mayer's and Helmholtz's – went almost unnoticed by Thomson and the others until well into the 1850s. When Thomson finally read Helmholtz's paper, he recognized the importance of Helmholtz's work and began citing the German professor's experiments as evidence for the new science of energy. Helmholtz, for his part, became one of the most prominent and enthusiastic German supporters of energy physics. Mayer's work met a slightly different fate. Although a few supporters (most notably the London physicist John Tyndall) who had read Mayer's paper tried to argue that Mayer and not Joule had first put forward the conversion of work into heat, Joule and his friends argued that Joule's work was by far the more impressive. Mayer had formulated an idea while Joule had provided evidence supporting it through rigorous experimentation. A century later, the Nobel Laureate Richard Feynman stated:

> There is a fact, or if you wish, a *law*, governing all natural phenomena that are known to date. There is no known exception to this law—it is exact so far as we know. The law is called the conservation of energy. It states that there is a certain quantity, which we call energy, that does not change in manifold changes which nature undergoes. That is a most abstract idea, because it is a mathematical principle; it says that there is a numerical quantity which does not change when something happens. It is not a description of a mechanism, or anything concrete; it is just a strange fact that we can calculate some number and when we finish watching nature go through her tricks and calculate the number again, it is the same.[1]

By this time, Joule was already entrenched in the public mind as the man who had established that work could be converted into heat, and Mayer's obscure paper had little chance of overthrowing Joule. But one wonders which man would have gotten credit for this fundamental idea in science if William Thomson had not been sitting in the lecture hall in Oxford on the day Joule delivered his paper.

[1]Feynman, Richard (1964). *The Feynman Lectures on Physics*; Volume 1. U.S.A: Addison Wesley.

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