The Origins of Entropy

How Culture Influences Scientific Progress


Sadi Carnot

In the late 18th and early 19th centuries, the Industrial Revolution was well underway in England. Many new types of heat engines had been invented. These new machines offered increased power and efficiency and were used to cheaply produce large amounts of goods. With these new machines came questions about their nature: why did the steam engine, the water wheel, or any other machine *work*? Why were certain engines more efficient than others? And how could machines be made more efficient?

The desire to better understand machines often stemmed from a fear of falling behind other nations. For instance, French engineers saw the advanced skills and technologies of the English and worried that France was falling behind in industrial know-how. The Industrial Revolution brought on an obsession with increased power and efficiency of machines. This obsession with power and efficiency would drive investigation in science, particularly the field of thermodynamics - the study of heat and energy.

Many people wrongly conflate science and technology. 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, is often essential for assisting in science research. In this historical story, notice how new technologies prompted scientific questions. Science and technology, while different disciplines, are so intertwined that *technoscience* is sometimes used to describe their interaction.

Two ideas dominated early 19th century debates concerning the nature of heat. Some natural philosophers argued that heat, or “caloric,” was a weightless fluid that flowed between objects. Others argued in favor of the dynamical theory of heat, which stated that heat was related to particle motion.

Though such discussion of heat were important for the emerging field of thermodynamics, the scientific investigation of heat was largely driven by engineering and industrial concerns with the efficiency of steam engines. To understand the origin of many important science ideas regarding heat and energy, we must revisit the Industrial Revolution of the early 19th century.

The arrival of new, high-pressure steam engines around 1800 spurred many new questions about engine principles. Making use of pressures far exceeding atmospheric pressure, these machines increased the power of engines. Engineers were particularly interested in understanding the 'expansive' processes in these engines. In older engines, steam was constantly injected into the cylinder in order to compress the piston. In the 'expansive' models, less steam was injected. Instead, the steam was allowed to expand in the cylinder, thus doing the same work with less steam. The term 'work,' first articulated in the late 18th and early 19th centuries, represented a 'quantity of action' equal to the product of force and distance.

Beyond 'quantity of action,' engineers were concerned with engine *efficiency*. The efficiency of an engine is the ratio of the input of heat and output of work. Without a conversion factor between heat and work, calculating efficiency was difficult. Engineers instead relied on the ratio between input of fuel and output of work, such as foot-pounds per bushel of coal. Many who studied engine efficiency studied the water wheel because its efficiency was easier to quantify and conceptualize than that of the steam engine.

Water wheel efficiency was calculated by observing the speed of incoming water, the size of the wheel, and the work produced. Lazare Carnot (1753-1823) discussed water wheel inefficiency in his 1783 *Essay on machines in general*. Lazare argued that the 'turbulence' and unused water motion should be minimized in order to maximize the efficiency of a water wheel. While the innovations in heat engines were important stimuli for further research, 'older' technologies such as the water wheel served as models through which to discuss efficiency and work. Indeed, Sadi Carnot (Lazare's son) would later reference the water wheel in his treatise on engines, *Reflexions* that was published in 1824.

Despite his marginal status in the mainstream engineering practice, Sadi Carnot shared concerns about the practical problems of steam engines. Carnot's concern was not with the resolution of whether heat was a material substance (caloric), or whether it was related to the motion of particles that made up matter — though he sided with the first option. What preoccupied Carnot instead were measurable macroscopic quantities, like pressure, temperature, heat, and work. Like other French engineers, he was concerned that France was falling behind the torrid advance of British industry. He believed that the 'haphazard' nature of improvements to heat engines was due to the lack of systematic knowledge about the engine's inner workings. Carnot thought that if one understood the underlying theory of steam engines, then one could systematically make improvements to engine work output and efficiency. Carnot's goal for the *Reflexions* was to create a complete theory of heat engines. Furthermore, Carnot believed this theory should rely only on general principles and not require any reference to the particular substance at work in the engine.

!

Carnot claims that a more basic understanding of the underlying principles of nature will help engineers create improvements in engine performance. He is seeking to understand the natural world to advance technology. This kind of science research is referred to as applied research. Scientists also conduct basic or pure research which is undertaken solely to learn more about the natural world without concern regarding whether or not that knowledge will advance technology. While basic/pure research often draws the ire of those concerned about potentially wasteful spending, it often creates a broad base of knowledge upon which other scientists can make connections they otherwise could never make, and often results in the creation of technology that profoundly changes the world. History makes clear the importance of both basic/pure and applied scientific research for technological advancement.

Carnot produced a number of important insights. First, while a heat source was clearly important for the operation of the engine, the presence of a *cold* source was just as important. What caused the production of useful mechanical work was the movement of heat from heat source to cold sink. Carnot often used the analogy of water wheels to explain his ideas. Because he subscribed to the caloric theory of heat, he imagined that heat flow from hot to cold sources was akin to the flowing of water through a water wheel from 'high' to 'low'. Just as water was 'conserved' and not consumed in the water wheel, so too was caloric conserved. Thus, one source of inefficiency was any movement of heat without the production of work. Again arguing by analogy, Carnot claimed that the waste of heat was like the wasted motion of water in a water wheel. If water fell without spinning a wheel, or if the water didn't optimally interact with a wheel's buckets, motion would be wasted and thus work output would be inefficient. Similarly, if heat were transferred to the surroundings without doing work, engine efficiency would be compromised.

Another key insight of Carnot's was that an engine's maximum efficiency only depends on the difference in temperature between heat source and heat sink. Carnot therefore determined that the engine's working substance didn't matter at all. Whether steam, air, or some yet undetermined substance, the *limits* of efficiency were the same. With these understandings, Carnot imagined an ideal 'perfect' engine, an engine that was *reversible*. By running the engine backwards, work could be used to transfer heat from the surroundings to the heat source. Carnot used the idealized “Carnot cycle” to describe the operations of a reversible engine. An ideal, reversible engine assumed no friction. The reversible engine was the 'limit' to an engine's productivity and efficiency. The reversible engine, though theoretical and not practically achievable, was the best possible engine, and thus a target to for which to shoot.

!

The role of idealization in science is often overlooked. In order for laws of science to be invariable relationships that apply throughout the universe, idealization is necessary. Then, when working with real objects, adjustments must be made taking into account how far the situation deviates from the idea. This approach is at odds with common sense thinking, but it results in knowledge that can be used widely rather than having to develop different laws for every unique situation.

Carnot's work was largely unheralded, possibly due to his position between the domains of academic physics (basic science) and engineering. He also used no calculus, although Clapeyron did include calculus when he reformulated Carnot's work in 1834. Carnot's ideas also relied on the caloric theory of heat; a position that was becoming increasingly difficult to support. Part of the reason for the decline of the caloric theory was the work of James Prescott Joule (1818-1889), an amateur gentleman scientist. Joule was in favor of the dynamical theory of heat, which claimed that heat was a form of motion. Because work could produce motion, Joule thought that heat could be transformed into work and vice versa.

Joule was the son of a Manchester brewer. Educated by private tutors such as the famous chemist John Dalton, Joule initially had little status in the scientific institutions of his day. Joule, supported only by his own means and interests, was an amateur scholar with no academic affiliations. Joule began research on the relationship between heat and work in 1843. At this time Joule was interested in the heat produced by fluid friction. In his investigation, a paddle-wheel was attached to a system of weights; when the weights were raised and dropped, the paddle-wheel agitated a tank of water. Using precise thermometers and skills obtained from his brewing background, Joule measured the slight changes in temperature of the water due to this mechanical agitation. Comparing this measure of heat produced by the paddle-wheel to the work done by the machine, Joule was able to calculate the "mechanical equivalent of heat." Joule published "On the Mechanical Equivalent of Heat" in January 1850 detailing the conversion factor between heat and work. This connection between the motion of the paddle-wheel and the heat of the water further convinced Joule that heat was a form of motion. Joule cited his own experiments as evidence for the dynamical theory of heat.

Notice Joule's background in brewing provided him with tools and knowledge with which he could investigate his ideas regarding heat and work. Scientists, like everyone else, draw on their prior knowledge and experience when approaching new problems.

1. Joule began his work in 1843, but did not publish his work until 1850. Many people think science is a quick process and that scientists develop ideas quickly. Using Joule and other examples from this story, why do you think science ideas often take years or even decades to develop and become accepted?

Because of the skills and precise instruments required for such investigations, many of Joule's contemporaries couldn't replicate his research. Joule's status as an outsider to the community didn't help either. Joule's findings needed help to acquire credibility, and Joule received this aid from William Thomson. Thomson, professor of natural philosophy at Glasgow University, was the dominant figure in British science in the second half of the 19th century. He worked on many topics, including heat, electricity, and magnetism. He also worked on the first transatlantic telegraph. Thus Thomson's support for Joule's theories was crucial for their credibility among the scientific elite. Though Thomson couldn't repeat Joule's experiments exactly, he decided that a more blatant exhibition of the claims would be useful.

James Prescott Joule

Thomson upped the scale of the paddle-wheel experiment, using large weights and wheels. Thomson nearly boiled water with this set up, exhibiting Joule's effects on a large scale.

2. Although Joule had evidence for his ideas and conclusions, they were not initially accepted. Factors such as his reputation and lack of available technology limited others' willingness to accept his ideas. While we would like to think scientists accept ideas based solely on evidence, other factors impact their decisions. Why would scientists' inability to replicate Joule's work along with his being an outsider impact the reception of his work?

Though Thomson supported the idea that mechanical work could be converted into heat, as well as the conversion factor, he wasn't sure about the opposite conversion of *heat into work*. This was due to his loyalty to the results and arguments of Sadi Carnot. Thomson's work on the absolute temperature scale, the Kelvin scale, was constructed using Carnot's ideas. Thus, Thomson didn't want to abandon Carnot's work. Yet, supporting Joule's work seemed to clash with his support for Carnot. Carnot's work, as detailed above, was predicated on the *conservation* of heat; heat 'fell' from the heat source to the cooler surroundings, just like water falls through a water wheel. This falling action was what produced work, and the heat (or the water) was neither consumed nor destroyed. On the other hand, Joule suggested that heat could be created or destroyed during the consumption or production of mechanical work.

Thomson had another, more pressing problem. If the action of heat falling from hot to cold produced work, what happened to this 'potential work' when the heat fell from hot to cold without a machine in place to produce work? In terms of the water wheel, if water fell a particular distance without generating work, what happened to this productive potential? In Thomson's thinking, since force could neither be created nor destroyed, this mechanical effect had to have gone somewhere. In Thomson's words:

> 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.

Thomson's concern with waste of potential useful work and the efficiency of engines likely reflected his social and cultural background. Though Thomson was primarily an academic, situated within mathematical physics, he also had connections to industry and engineering as a result of his location in Glasgow, an important port that showcased innovations to steam powered ships. Thomson's concerns with waste and efficiency likely stemmed in part from the same concerns as other engineers, concerns that had driven the work of engineers like Carnot. More efficient engines would produce more work with less fuel, thus producing cheaper power and cheaper goods.

Likely fueling his concern with inefficiency was Thomson's religious beliefs. As a devout Presbyterian, Thomson believed any waste of nature's gifts was inherently sinful. Humans were supposed to use nature's powers to improve society, and anything less was a 'sin of dissipation.' Thomson believed that the waste of useful work was a component of the inherent imperfections of humanity. The 'perfect' and ideal reversible engine was to the real, irreversible engine as God was to humans. Humans (and their machines) could strive for the ideal, but never quite attain it. These religious sentiments help explain why Thomson and others were so concerned with waste and efficiency. In short, religious and philosophical concerns as well as economic, scientific, and industrial concerns caused fixation on efficiency. Thomson was stuck between the ideas of Joule and Carnot.

3. Notice that scientific progress in this story seems to be affected by technological demands, economic concerns, and personal beliefs. All of these factors could be summarized as cultural influences. Using examples from the story, how might culture influence science and scientists? While subjective cultural factors do impact science in both positive and negative ways, in the end, how does the scrutiny of the wider scientific community ensure the validity of knowledge developed about nature?

Later in 1850, Rudolf Clausius, suggested how Joule and Carnot's positions could be reconciled. In his "On the Moving Force of Heat and the Laws of Heat which may be Deduced Therefrom", Clausius put forward how accepting interconvertibility did not require rejecting Carnot's main idea. However, the conservation of heat had to be abandoned. Clausius argued that both conversion and transmission of heat occurred in steam engines. Some heat was converted into work, while the rest transferred from the heat source to the cold source. Both processes were required! Clausius pointed out that the synthesis of Carnot and Joule's ideas required a 'natural direction' for phenomena. This natural direction was found in the 'natural' movement of heat from a hot body to a cold body enshrined in Carnot's focus on temperature difference between heat source and sink. Heat naturally tends to flow from hot to cold bodies, but not from cold to hot bodies unless some external driving force or work causes this unnatural transfer. Clausius noted that "Heat can never pass from a colder to a warmer body without some other change, connected therewith, occurring at the same time." This was Clausius's formulation of what we now accept as the *second law of thermodynamics*.

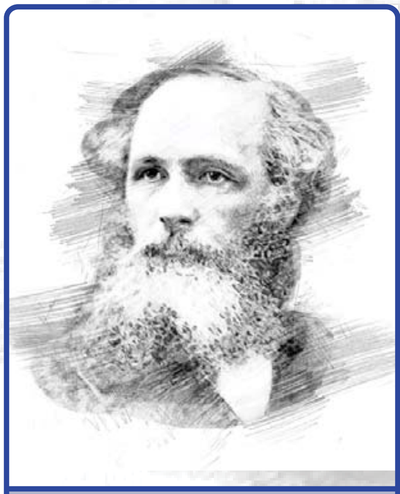
In later works, Clausius formulated the second law mathematically, producing the relation $\Delta S = Q(1/T_2 - 1/T_1)$, where Q represented the heat transferred from heat source at temperature T_1 to cold source at temperature T_2. S represented a term Clausius called "entropy," first introduced in 1865. This entropy was a measure of the heat "lost" irrecoverably, or a measure of a systems *inability* to do work. Clausius's 1865 formulation of the second law claimed "the entropy of the universe tends to a maximum." In other words, the entropy in the universe can either stay the same or increase, but can never decrease. This tendency implied a beginning minimum of entropy, an implication that Thomson seized upon, as we shall see.

Thomson eventually supported Clausius's line of thinking in his 1852 "On the dynamical theory of heat." However, the notion that both conversion and transfer occur in engines hit at Thomson's second problem: what happened to this 'lost' potential work, dissipated as heat or friction? If some heat fell into the cold reservoir without being converted into work, what happened to the 'potential' for work that the heat represented? In 1852 Thomson explored his concerns in "On a universal tendency in nature to the dissipation of mechanical energy." He again noted that in real engines a certain amount of heat would flow to the cold reservoir without creating work. This 'waste' was unavoidable in the imperfect machines made by imperfect humans. However, the heat wasn't lost irrevocably to nature – the energy present in the heat not converted to work was simply transferred to the cold source. Energy was conserved, as the First Law would predict. The problem of waste lay therefore in *human imperfection*.

This insight had implications for engineering practice and for Thomson's theological and philosophical views about the 'progressive' aspect of nature. By progressive, Thomson meant that everything moved towards a particular endpoint, whether that endpoint was the natural movement of heat from hot source to cold source, or the dissipation of the energies of the universe. Only God could create or destroy, and only God could reverse the inevitable progression of the universe – a progression marked by the dissipation of heat and the waning potential for human access to work. This reinforced the Presbyterian 'fall' of nature, as the universe wasn't perfect, wasn't infinite, and wasn't unending. Furthermore, the directionality of entropy suggested that the perfectly ordered universe had existed at some beginning point, willed into creation by an omnipotent God. Thus, the laws of thermodynamics, and especially entropy, were conceived as compatible with the Christian universe of Thomson and his contemporaries.

4. While many scientists have strong theological beliefs that influence their thinking, as Thomson clearly did, they do not use these supernatural beings in their scientific explanations. While Thomson linked theological implications to his understanding of heat, he did not simply resort to "God did it." This is not very different from our own lives. When our car breaks down, we want a mechanic to provide a natural, not supernatural, explanation. Why is this the same in scientific explanations?

Micro level considerations, dealing with the interaction of tiny particles, provided other insights about the nature of the second law and entropy. Thomson and other physicists, including James Clerk Maxwell (1831-1879), wanted to know how the motion of microscopic particles could explain the second law. A key problem for these physicists was the reversibility of mechanical laws. Imagine water being poured out of a glass onto a table. After the water was spilled, if all the trajectories of the water particles were reversed exactly, the water would gather back on the table and spring back into the glass. Such an action did not break any physical laws; however, such a peculiar action in nature is never observed. Water falling out of a glass seemed to have a 'natural direction' just as heat had a 'natural direction' of moving from hot to cold. What then seemingly 'guaranteed' this directionality of microprocesses?



James Clerk Maxwell

Maxwell addressed this question with a thought experiment, later called "Maxwell's demon." Imagine two separate containers, systems A and B, filled with particles moving at various velocities, bouncing off each other and the walls of their container chaotically. According to the dynamical theory of heat (and the kinetic theory of gases), the average velocity of the particles in a system is directly related to the temperature of that particular system. Next imagine that A and B are connected by a small door. This door remains open, allowing some particles to move back and forth between containers as they bounce around. Next imagine a small demon of high intelligence observed the containers and was able to control the opening and closing of the door (without any energy input into the system). This small demon would watch the particles bouncing around in systems A and B.

When he saw a particularly fast particle in A whiz towards the door, he would open the door to let it move from A to B. When he saw a particularly slow particle in B move towards the door, he would open it, allowing the particle to move from B to A. Over time, the average velocity of the particles would increase in B and decrease in A. Thus, the temperature of B would *increase* with no input of work or energy from the outside. This was in direct contradiction to the second law of thermodynamics, which, according to Clausius and Thomson, did not allow the unaided or spontaneous transfer of heat from cold bodies to hot bodies.

The explanation for this seeming contradiction again relied on the limits of human intelligence and perception. If humans could act like the 'demon,' then work could be recovered from cold bodies through this manipulation of individual particles. The second law thus wasn't absolute; it was only a statistical likelihood, a function of human inability to control microscopic motions. Thus, water jumping off of a table, or heat moving from a cold body to hot body, was not absolutely impossible. It was just incredibly unlikely. The 'natural' direction of processes was only natural relative to human ability. In Clausius's terms, entropy (inability to do work) could spontaneously decrease in a system, though such decrease was just as unlikely as heat flowing unaided from an ice cube to a furnace.

!

Many people believe all scientists use "the scientific method." Yet, in no version of the scientific method will you see "imagine a demon with a frictionless door." Maxwell's thought experiment is not unique. Scientists such as Einstein and Galileo used thought experiments. Scientists are not limited to one scientific method, they will use any means necessary to gain greater understanding of the natural world, including imaginative thought experiments. This is why the physicist and Nobel Laureate, Percy Bridgman, once claimed that "the scientific method, insofar as it is a method, is nothing more than doing one's damnedest with one's mind, no holds barred." Scientists tend to use methods and approaches that will shed insight onto a research problem.

As the 19th century continued, the concept of entropy found applications in areas other than engineering. For example, entropy became a foundational concept for understanding chemical reactivity and thermochemistry. Scientists in various places and disciplines developed entropy from its beginnings as an engineering concern with engine efficiency to a general conception of a system's capacity for work, from a statistical likelihood to a chemical concept useful on the laboratory bench.

Science ideas often have far-reaching applications that promote further advances in science and technology. We can and must proceed confidently with the best available scientific knowledge we possess, knowing that a strength of science is that its ideas can, if required, be modified to better explain natural phenomena.

The Origins of Entropy: How Culture Influences Scientific Progress
written by Robert Schombs, Jerrid W. Kruse, and Michael P. Clough

Partial support for this work was provided by the National Science Foundation's Course, Curriculum, and Laboratory Improvement (CCLI) program under Award No. 0618446. Project Principal Investigator: Michael P. Clough. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.