A Matter of Degrees

Conceptualizing Temperature and Heat

Daniel Gabriel Fahrenheit

In 1776, as the British Empire struggled against its rebellious subjects for control over the American colonies, the Royal Society of London convened a commission to resolve a conflict within its ranks regarding a matter of utmost importance. For more than a century, the Society's membership had committed itself to the exploration of the natural world, emphasizing the value of quantitative measurements which could be subjected to mathematical analysis. Such an approach required standardized instruments whose measurements could be trusted. However, despite relative agreement about the accuracy of existing clocks, measuring sticks, and systems of weights, the British scientific community could not say the same about its thermometers. Edmond Halley, the astronomer known for his namesake comet, had lamented in 1693 that he could never tell what the marks on the side of his thermometer represented because each instrument was made “by Standards kept by each particular Workman, without any agreement or reference to one another.” In short, no established scale existed to measure temperature. Although Halley and his successors on the Royal Society had attempted to resolve this problem, the matter remained unresolved until the commission established the boiling point of water as a standard reference point for future instruments.

> !
>
> **The effort to create a standardized temperature scale is really a technological problem, but it is crucial for assisting with investigating and understanding the natural world. 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. Science and technology, while different disciplines, are so intertwined that the term *technoscience* is sometimes used to describe their interaction.**

Although seemingly trivial, this problem was significant for several reasons, particularly when scientists began to think seriously about the concept of heat. Unlike measurements like length or mass, temperature is not based upon a visible phenomenon. Although we have an intuitive appreciation of the difference between hot and cold, no quantitative statements about temperature can be made without a thermometer. Further complicating matters at this time was the uncertainty regarding what precisely is measured by a thermometer. Scientists across Europe were divided as to how best to understand heat—as an invisible fluid, undetectable except for its tendency to warm up other substances, or a physical phenomenon associated with matter in motion. Although today's scientists accept a version of the latter, its ultimate success was neither obvious nor immediate. In fact, both approaches provided scientists with a useful framework for interpreting heat-related phenomena, and each played a vital role in the creation of the modern field of thermodynamics.

Early Developments in the History of Thermometry

The systematic study of heat can be traced back to efforts of philosophers living in the Eastern Mediterranean beginning in the fourth century BCE, when Aristotle listed fire as one of the four fundamental constituents of the natural world. Aristotle, however, did not attempt to create a gradated scale indicating the relative temperature of a substance. Such an advance did not occur until several centuries later, when the Roman physician Galen (129-200 CE) suggested the creation of a nine-point scale indicating deviations from normal body temperature. Galen's medical theories would remain popular until the late seventeenth century, but his temperature scale existed solely as an abstraction since none of his disciples used it to create a measuring instrument. A few mechanically inclined individuals such as Philo of Byzantium and Hero of Alexandria constructed devices driven by the expansion of steam which could be used to detect changes in gas temperature. However, those tools could at best be considered “thermoscopes,” because unlike thermometers, they did not include a numeric measurement scale, and they could not be used to make quantitative measurements.

These ancient investigations provided the inspiration for the creation of the first modern thermometers in the early 17th century. An interest in Galenic medicine, for example, prompted Santorio Santorre, professor of medicine at the University of Padua, to order the construction in 1612 of “a certain glass instrument,” consisting of a bulb attached to a cylindrical stem which was then placed in a vessel of

Daniel Gabriel Fahrenheit, adapted from digital likeness created by Tomasz Ziółkowski and Jerzy Proficz.

water. As the temperature changed, the air in the bulb expanded and contracted, causing the water level in the tube to rise and fall. Santorio was then able to use his device to compare extremes in temperature such as snow or a candle flame. Another of Santorio's colleagues at Padua, the physicist Galileo Galilei, constructed a similar device after reading an Italian translation of Hero's *Pneumatica*. Santorio and Galileo's instruments had different scales, but operated on the same principle, the ability of heat to alter the pressure of the air inside a tube in comparison to that of the surrounding atmosphere. Soon after the invention of the barometer by Galileo's student Evangelista Torricelli, however, the idea that air pressure also changed depending upon one's altitude and the prevailing weather conditions became clear. The standardization of thermometric measurements would require a shift in instrument design.

The quest for an accurate thermometer gained a powerful new ally in 1657 when Duke Ferdinand II of Tuscany founded the Accademia del Cimento (Academy of Experiment) in Florence, dedicated to expanding the mathematical and experimental program advocated by Galileo. Unlike the royal patrons who sponsored Britain's Royal Society or the French Académie Royale des Science, Duke Ferdinand took an active role in his Accademia and provided them with space to work in Florence's Pitti Palace. The Duke also developed an improvement upon previous open-air thermometer designs, calling upon the artisans in his family's workshop to construct a sealed thermometer, consisting of a closed glass tube with a bulb filled with “spirit of wine” (distilled ethyl alcohol).

The expansion and contraction of the enclosed liquid was measured using a scale dividing the thermometer into fifty smaller subdivisions. The Accademia's membership hailed Duke Ferdinand's new instrument as a success, and arranged for new ones of various shapes and sizes to be manufactured. The Duke went so far as to hang ornate thermometers of all different shapes and colors in every room of his palace. He also arranged for the publication of an account of the Accademia's research into heat, including detailed instructions so that glassblowers elsewhere could create their own high-quality thermometers.

Though the Accademia's thermometers provided a template upon which other natural philosophers could base their instruments, even the most sophisticated Florentine thermometers possessed flaws which soon became evident. For example, although the Accademia recommended the use of alcohol in their thermometers, they knew that the distillation process resulted in a liquid whose density varied from batch to batch, making the readings on two otherwise identical thermometers no longer coincide. In addition, alcohol evaporates at a lower temperature than water, inconveniencing those scientists investigating high temperature phenomena. Fortunately, both of these problems could be remedied by replacing alcohol with another substance, typically mercury or air. Arguably a more serious design flaw was the Accademia's method for determining the size of the degree divisions on its thermometers. The Accademia's calibration method consisted of finding the space between two fixed marks and dividing it into a number of equal parts. Unfortunately, its choice of reference points, “the most severe winter cold” and “the greatest summer heat,” were remarkably vague. If temperature measurements were to possess any value for future investigators, the size of a degree had to remain constant, which meant scientists would need to find phenomena which only occurred at specific temperatures.

Prior to the Royal Society commission's decision to adopt the boiling point of water as a fixed point, its members and correspondents suggested a variety of alternatives. While a few, like Robert Hooke, believed they could simplify the process by using a single fixed point (e.g., the temperature at which water froze or boiled) and measuring degrees based on the fractional expansion or contraction of a chosen fluid, most continued to suggest two fixed points. In 1701, for example, Isaac Newton endorsed using “the heat of the air in winter when the water begins to freeze” and “blood heat” (i.e., the temperature of a human body) as reference temperatures. Other proposals were more outlandish. Joachim Dalencé suggested the temperature at which butter melted, and both Edmond Halley and French mathematician Philippe de La Hire theorized that air's temperature in deep caves or cellars would provide a better low temperature touchstone than the freezing point of water.

To illustrate the difficulty in identifying phenomena with truly fixed temperatures, consider the boiling point of water. Atmospheric pressure can have a significant impact on boiling point, which is why water boils at lower temperatures at greater elevation. Scientists in the 18th century were also aware that the point that water boils can be significantly affected by the type of material holding the water, how fast the water is heated, the amount of air dissolved in the liquid, and whether objects are placed in the water. Even when keeping pressure constant, the aforementioned factors create such discrepancies in the boiling point of water that Isaac Newton's proposed temperature scale from 1701 (Figure 1, *see page 3*) had two lines to indicate a *region* of temperatures at which water boiled instead of simply one point. The issue of reliably measuring the boiling point of water was not resolved until the late 1700s, when the Royal Society recommended measuring the steam immediately above the water instead of the water itself. By doing so, the range of temperatures for the boiling point of water was significantly decreased, even when the liquid water was superheated.

1. Note the creativity required by scientists as they struggled to create a valid and reliable instrument to measure temperature. After reading the remainder of the story, describe another example of scientists using creativity during the course of their investigations.

By the mid-18th century, the plethora of possible reference points and thermometric scales had been narrowed to two. The first of these was created by the Polish-born instrument-maker Daniel Gabriel Fahrenheit. Fahrenheit was orphaned at the age of fifteen when his parents died from mushroom poisoning. Shortly afterwards his relatives apprenticed him to a bookkeeper, but his interest in natural philosophy, particularly the construction of scientific instruments, led him to abandon his apprenticeship so that he could travel across Europe to hone his skills.

Figure 1. *An early thermometer with four scales. The scale on the bottom was created by Isaac Newton.*

In 1708, Fahrenheit arrived in Copenhagen, where he met with Danish astronomer Ole Roemer. Roemer had previously devised a sixty degree temperature scale where 0° was the temperature of a mixture of ice and salt and 60° was the boiling point of water. On this scale, 7.5° would be the melting point of ice and blood heat would be 22.5°. Fahrenheit liked aspects of Roemer's scale, but found it "inconvenient and inelegant on account of the fractional numbers." He shifted the melting point of ice up to 8° and the blood-heat mark to 24° before quadrupling his numbers so that the amount the mercury expanded between each degree in his thermometers coincided with those being used by Boyle and Newton. The net result was a scale where water's freezing point was 32°, the temperature of the human body was 96°, and the boiling point of water, though not one of Fahrenheit's initial fixed points, corresponded to 212°.

!

Notice how Fahrenheit drew critical insight regarding the design of his temperature scale from colleague Ole Roemer. Science is often wrongly thought to be a solitary activity, but most scientists work in teams to design and conduct investigations, and regularly attend conferences. As you continue reading, look for other examples of collaboration between scientists.

Scientists in Britain and the Netherlands quickly adopted Fahrenheit's temperature scale, while an alternative system eventually won out in France and the rest of Europe. As early as 1710, a Swedish scholar named Elvius had proposed the use of a centigrade system, where the values of 0° and 100° were assigned to the freezing and boiling points of water. The man whose name would come to be associated with the centigrade system, Anders Celsius, was also Swedish. The son and grandson of astronomers, he had participated in expeditions to Lapland intended to confirm the extent of Earth's curvature and became frustrated with the instruments available to measure cold.

He obtained a thermometer from St. Petersburg and etched a new scale on it, similar to Elvius' proposal, but with the boiling and freezing points reversed. In other words, 0° was the temperature at which water boiled and 100° was the temperature at which it froze, a reversal that might have resulted from Celsius' interest in how cold, rather than how hot, objects were.

After Celsius' death, his successor at the University of Uppsala, Martin Stroemer, simply reversed Celsius' numeration, creating the modern centigrade temperature scale. The system, eventually named after Celsius, grew in popularity, especially after the widespread adoption of the metric system encouraged the use of decimal units. However, while decimal units make changing between different units more convenient, such as kilometers to meters, these conversions were not needed in thermometry. Furthermore, the Fahrenheit system had its own advantages. The Fahrenheit scale has 180° (212° – 32°) between the boiling and freezing points of water, for example, while the Celsius system has only 100° (100° – 0°), meaning that one could obtain more precise temperature readings in Fahrenheit without resorting to fractional degrees.

The Schism between Heat and Temperature

Although some doubt remained regarding which scale was more appropriate or whether certain physical phenomena always occurred at a constant temperature, the existence of standardized thermometric scales meant that scientists could now make increasingly meaningful comparisons of their data which would assist in coming to better understand heat. Newton, Boyle, and Fahrenheit had each approached the subject, but until 1759, no distinction was made between the amount of heat contained in a substance and its temperature. That year, however, a Scottish scientist named Joseph Black began a series of investigations that would significantly alter how chemists and physicists wrote, spoke, and thought about heat.

Figure 1, Photo accessed from www.sites.hps.cam.ac.us/boiling/Adams_large.jpg.

Black was a professor of medicine and chemistry at the University of Glasgow. He was keen to build off of the work of Dutch physician Hermann Boerhaave, a friend of Fahrenheit's who was interested in how heat behaved in liquid mixtures. Boerhaave requested that Fahrenheit mix together two equal volumes of water at different temperatures. As might be expected, the resulting temperature of the mixture was exactly halfway between the two initial temperatures (e.g., mixing equal volumes of water at 60°F and 80°F resulted in water with a temperature of 70°F). Boerhaave then altered the investigation by replacing the water in one container with an equal volume of mercury.

Black noted that Boerhaave assumed that "the quantities of heat required to increase the temperatures of different bodies by the same number of degrees were directly proportional to the quantities of matter in them…and therefore when the bodies were of equal volumes, that their quantities of heat were proportional to their densities." Since mercury was approximately 14 times denser than water, the quantity of heat needed to warm mercury by 1°F should be 14 times larger than that for water. However, Black noted that, "the quicksilver…never produced more effect in heating or cooling...than would have been produced by water of the same initial temperature as the quicksilver, and only two-thirds of its volume," which directly contradicted what Boerhaave had expected.

Boerhaave was at a loss to explain the results of the experiment. Black, however, was familiar with another experiment conducted several years later by a British Army officer, George Martine. Martine had placed equal volumes of mercury and water at equal distances from a large fire and tracked the rate at which the temperature of each substance increased. "Before these experiments were made," Black observed, "it was supposed that the time needed for the quicksilver to heat or cool would be longer than for an equal volume of water, in the proportion of 13 to 14 to one."

In fact, however, the mercury warmed nearly twice as fast as the water. Black concluded that the results of the investigations by Boerhaave, Fahrenheit, and Martine shared a common cause: less heat was required to produce a given temperature rise for mercury than an equal volume of water. "The quicksilver therefore, may be said to have less capacity for the matter of heat." Black put forward the idea that heat does not distribute itself among bodies in proportion to their density or volume, but rather *based on a characteristic property of each substance, its heat capacity*. Every substance had a different heat capacity, and therefore required a different amount of heat to raise its temperature the same amount.

!

Note that not all scientific investigations are classified as experiments. Experiments require the manipulation of variables to explore the effects of those changes, such as Boerhaave and Fahrenheit changing the types of materials they combined to see the impact doing so had on the final temperature of the mixture. Scientists have many other tools at their disposal to explore the world though, including observational studies, which involve carefully observing phenomena and recording the results.

Through the formulation of heat capacity, Black had taken the first step in distinguishing between the quantity of heat present in a substance and its temperature. He expanded upon this idea in his study of heat's involvement in state changes like boiling or melting. Earlier scientists, most notably French physicist Guillaume Amontons had observed that when water boiled, its temperature remained constant, even though heat continued to be applied to the liquid. "However long and violently we boil a liquid," Black observed, "we cannot make it in the least hotter than when it began to boil. The thermometer always points to the same degree, the vaporific point of that liquid." Black concluded that the heat added to water during boiling was converting the liquid into a vapor. Since the temperature of the water did not change during that time, black called the invisible heat being added "latent heat."

2. Observations and data may sometimes seem to have straightforward explanations, but they do not tell scientists what to think. For example, Black was not the first scientist to note that the temperature of water does not change once it begins to boil. If data simply told scientists what to think, then Amontons and others should have developed the idea of latent heat before Black did. Instead, scientists draw upon their knowledge and experiences along with creative insights to put forward ideas that make sense of the data. What is another example from what you have read thus far that demonstrates data do not tell scientists what to think?

Two Competing Explanations of Heat

Black recognized that the concepts of heat capacity and latent heat would have profound ramifications on the longstanding efforts of natural philosophers to provide a theory for thermal phenomena. At the time, the European scientific community was divided into two major schools of thought, each of which claimed to possess a more comprehensive explanation for the cause of temperature changes: gas expansion, and state changes. On one side of the debate were those who believed the ultimate cause of heat was matter in motion. On the other were scientists who felt that heat consisted of invisible particles of heat capable of permeating ordinary matter and raising its temperature. Black himself was uncertain which of these two approaches best explained his results, noting that "our knowledge of heat is not brought to that state of perfection that might enable us to propose with confidence a theory of heat or to assign an immediate cause for it." Still, he felt that the inability to determine the quantity of heat present in a substance through a simple thermometric reading should be considered within each of these theoretical frameworks to see which one better explained it.

The idea that heat consisted of motion, Black observed, was based "chiefly on the consideration of several means by which heat is produced." In his 1620 treatise *De forma Calidi*, for example, Francis Bacon had highlighted several different ways to generate heat, including frictional contact, striking flint and steel together, and the traditional practice among blacksmiths of heating up metal by hammering it quickly on different sides. In every case, the increase in heat was associated with a mechanical force being applied to a substance. Robert Boyle would later claim this change reflected the increased motion of matter's constituent particles. While Black acknowledged the common-sense utility of considering heat as a kinetic process, his idea that different substances possessed characteristic heat capacities seemed to counter the notion that heat was "a tremulous, or other, motion of the particles of matter." If that theory were true, he suggested, denser substances, which contained more particles of matter, should possess higher specific heats. However, as Black had demonstrated, that was not the case with mercury, whose specific heat was less than water even though its density was greater. "I do not see how this objection can be evaded," Black wrote.

One might assume that Black's concerns regarding the theory that heat was matter in motion corresponded with wholehearted endorsement of the alternative theory that heat consisted of an invisible substance capable of altering the properties of ordinary matter. In fact, his stance was somewhat more complicated. "Heat is plainly something extraneous to matter," he commented, but later on he noted that objects did not increase in weight when heated. In other words, if heat was ultimately an invisible substance, it could not be detected in the same fashion as normal matter. Black noted that some "have attempted to remove this objection by supposing the matter of heat to be so subtle and tenuous that no quantity of it which we can collect together can have any sensible weight," but admitted that these claims were "ingenious, but they are not satisfactory." Therefore, Black concluded, while the idea of heat as a material substance was "the most probable of any that I know," at the time of his lectures, it remained "altogether a supposition."

Black's public agnosticism on the debate between those who thought heat was ordinary matter in motion and those who viewed heat as a separate invisible form of matter did not prevent other people from integrating his ideas into their own conceptual frameworks. This work proved particularly intriguing to members of the latter school of thought, most notably French chemist Antoine-Laurent Lavoisier and physicist Pierre-Simon Laplace. In their 1783 *Mémoire sur la Chaleur* (*Memoir on Heat*), these two men set forth the tenets of a new approach towards the study of heat, which became known as the caloric theory.

According to this model, heat consisted of a subtle, imponderable (i.e., weightless) fluid called caloric which could not be created or destroyed. Caloric particles repelled one another but were attracted to particles of ordinary matter. The physical sensation of heat was the result of caloric flowing from a hotter body to a colder one. While the concentration of caloric in a substance could be detected using a thermometer, Lavoisier and Laplace suggested that it could also combine chemically with particles of matter. This combined caloric could not be detected with a thermometer and could only be observed in chemical reactions or physical state changes where heat was absorbed or released.

!

In everyday speech, the word "theory" is synonymous with "guess," but in science, theories are explanations that help scientists make sense of a broad range of relationships between phenomena (i.e., scientific laws). Unlike the common usage of "theory," well established scientific theories have extensive supporting evidence. While scientific laws express relationships, scientific theories explain why those relationships exist, and they guide research by framing fruitful research questions, methods, and sense-making.

The caloric theory provided straightforward and powerful explanations for how heat behaved. Caloric particles' tendency to repel from one another explained both why heat flowed from warm bodies to colder ones and why materials expanded when heated. Different substances' characteristic heat capacities reflected variability in the amount of caloric they could absorb. In addition, the assumption that caloric should be treated as a chemical element capable of forming compounds with ordinary matter, as Lavoisier would explicitly claim in 1789, provided a means of accounting for Black's observations that a substance's temperature remained fixed during state changes; additional caloric reacted with ice to form liquid water, for example, becoming "combined caloric" which did not cause a sensible change in heat. The caloric model even provided explanations for phenomena that Bacon and his supporters had cited as evidence that heat was caused by motion. For example, hammering a piece of iron caused its temperature to increase, not because its matter was vibrating faster, but because caloric was being physically squeezed out of the metal like water from a sponge.

At a time when phenomena associated with electricity and magnetism were explained in terms of invisible fluids, that the caloric theory found a large number of supporters is unsurprising. As natural philosopher M.J. Brisson wrote in his *Dictionnaire de physique*, even if the alternative kinetic theory were correct, the caloric theory was "by far the simplest way to account for the heat of bodies." Some scholars even held out hope that the caloric theory might lend insight into a deeper connection between heat and other phenomena. This desire for theoretical unity even prompted Lavoisier and Laplace to collaborate with noted electricity expert Alessandro Volta to determine if electrical charge was produced during evaporation.

Rumford's Response: Opposition to Caloric

Yet despite the caloric theory's explanatory power and its potential to provide a common grounding for studies of heat, light, and electricity, a few natural philosophers refused to abandon the idea of heat as matter in motion. The most prominent of these holdouts was Benjamin Thompson, better known to his colleagues as Count Rumford. Rumford was born in Massachusetts, but fled to London after the American colonies declared independence from Britain. He acted as King George III's undersecretary of state for the colonies and also gained fame as an inventor who designed improved fireplaces and kitchens. In a curious intersection of the social and the scientific, he also spent time seducing, and eventually marrying Lavoisier's widow after the chemist was killed in the French Revolution.

Rumford's interest in caloric theory emerged in connection with his military responsibilities. In 1792, he organized a trial to determine how large of a gunpowder explosion would be required to rupture one of the Bavarian army's cannons. In a letter submitted to the Royal Society, he calculated that 55,000 atmospheres worth of pressure would be required to destroy the cannon's barrel, a force which he noted "depends solely on the elasticity of water vapour, or steam." Unlike Lavoisier, who "imagined that the force of fired gunpowder depends in great measure upon the expansive force of uncombined caloric," Rumford warned that "it is not only dangerous to admit the action of an agent whose *existence* is not yet clearly demonstrated, but it appears to me that this supposition is quite unnecessary."

This statement, published in 1797, marked the first shot in a campaign Rumford waged for the remainder of his life against the existence of caloric and in favor of the idea that heat and all of its effects could be explained solely by matter in motion.

Rumford's frustration with caloric was the tendency of its supporters to ignore the inconvenient or contradictory aspects of their theory. If caloric were a material substance, he argued, it should possess all of the properties of ordinary matter including mass and volume. Yet, when Rumford conducted a series of investigations tracking the weight of different liquids as they were repeatedly heated and cooled, no change in their weight was detected. "I think we may safely conclude," he wrote, "ALL ATTEMPTS TO DISCOVER ANY EFFECT OF HEAT UPON THE APPARENT WEIGHT OF BODIES WILL BE FRUITLESS." While supporters of caloric countered that heat was, along with electricity, magnetism, and light simply another example of a weightless fluid, Rumford felt that the results of another investigation would demolish their position.

The study in question centered around the origin of heat generated by friction. Supporters of caloric believed that heat resulting from friction was caloric squeezed out from the surface of two bodies. Rumford realized that if caloric could neither be created nor destroyed, as Lavoisier and Laplace had argued, then with sufficient friction one could cause all of the caloric to be drained from a substance. Taking advantage of his position as superintendent of the Munich arsenal, Rumford decided to test this conclusion. He utilized the same equipment used to drill holes into cannons to test whether the heat generated in the boring process was always the same, no matter how long the drilling continued.

To accomplish this task, he took a piece of metal discarded during the process of casting a cannon and shaped it into a cylinder. He then arranged for the metal cylinder to be fixed in place and surrounded with a small wooden box which could in turn be filled with water. After attaching a dulled bit to the normal drilling apparatus, he inserted the bit into the water-filled box and turned on the machinery. The horse-driven drill ground against the metal cylinder, generating heat in the surrounding water and eventually causing it to boil. Rumford measured the amount of time it took to heat the box of water several times and found that the supply of heat "appeared evidently to be inexhaustible." He concluded that "anything which any *insulated* body, or system of bodies, can continue to furnish *without limitation*, cannot possibly be a *material substance*; and it appears to me extremely difficult…to form any distinct idea of any thing, capable of being excited and communicated in these experiments, except it be MOTION."

3. Science is often wrongly portrayed in textbooks as a linear, step-by-step process called "the scientific method." Such depictions typically involve posing a hypothesis, conducting an experiment, analyzing results, and drawing conclusions. Much, but not all, research does include these processes, but not in any linear fashion. How does the work of scientists in this reading illustrate that research does not follow a linear step-by-step method?

Some textbooks have wrongly framed Rumford's cannon investigation as a decisive refutation of the caloric theory and an early antecedent for the modern kinetic theory of heat. Rumford's theory of heat, involving the vibration of stationary atoms sending out invisible waves of heat, is very different from the modern conception of heat caused by randomly moving particles. Furthermore, despite Rumford's confidence, most advocates of caloric theory did not find his arguments persuasive, as they noted the limited time that he had boiled water, and his evidence did not support the view that friction was an "inexhaustible" source of heat. In addition, Rumford's claim that heat was motion implied that electricity generated by friction could also be considered a form of motion, a position that no upstanding natural philosopher in nineteenth-century Europe would defend. Worst of all, Rumford's work could be interpreted as heat being created from nothing which was at odds with the principle of heat conservation that had been the foundation for investigations on the subject for over a century.

The solution to the last of these problems, replacing "conservation of heat" with "conservation of energy," would only become accepted thirty years after Rumford's death. A key figure in this transition, James Joule, who used a paddlewheel setup similar to Rumford's to quantify the relationship between heat and work, cited the earlier scientist's research as an inspiration. However, suggesting that caloric theory hindered the subsequent development of thermodynamics would be unfair. Caloric provided a cogent explanation for the discrepancy between heat and temperature and inspired innovative investigations among both supporters and opponents. While our current understanding of heat more closely resembles Rumford's ideal of matter in motion, the presence of terms like "latent heat" and "heat capacity" in modern textbooks reveals the continued debt that thermodynamics owes to the caloric theorists.

4. Despite Count Rumford's work, and numerous other investigations that were problematic for proponents of caloric theory to explain, kinetic theory was not widely accepted until the middle of the 19th century. A major strength of science is the ability of it to change in light of new evidence, but transitions to new ideas tend to happen slowly. Those slow transitions may seem like a weakness of science, but consider why scientists are rightfully wary of rapid change. Provide at least three reasons why a more cautious and unhurried approach to change is warranted.

A Matter of Degrees: Conceptualizing Temperature and Heat
written by Benjamin Gross, Alister R. Olson, 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.