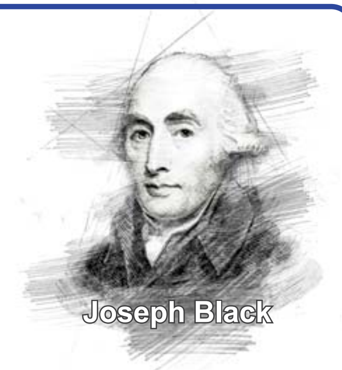
Calorimetry

Creativity and Invention in Science



In 1702, the Royal Society of London published an anonymous article which attempted to resolve a longstanding problem confronting the group's membership. For decades, the Society had dedicated itself to the task of exploring the natural world, and they emphasized the value of quantitative measurements that could be subjected to mathematical analysis. While relative agreement existed about the accuracy of existing clocks, measuring sticks, and systems of weights, the British scientific community could not say the same about its thermometers.

The Society's secretary, the astronomer Edmond Halley, had noted that one could never tell what the marks on the side of a given thermometer represented because each instrument was made "by Standards kept by each particular Workman, without any agreement or reference to one another." The aforementioned anonymous article attempted to resolve the issue by suggesting a standardized set of reference temperatures. The lower fixed point of this scale, "the heat of the air in winter when water begins to freeze," would be set at 0°. The higher fixed point, 12°, was set at "blood heat," and defined as "the maximum heat that the thermometer can attain by contact with the human body."

In hindsight, the difficulties of using body heat as a thermometric constant may seem obvious. After all, even a healthy human body's temperature can vary over time. Yet in the absence of standardized thermometers capable of precise measurement, blood heat was considered one of the more reliable possibilities for a reference temperature, as evidenced by the support of the Royal Society's most famous member and the author of the anonymous 1702 article: Isaac Newton. Newton abandoned his work on thermometry to pursue his interest in optics, but six years later an instrument maker named Daniel Fahrenheit would use body temperature, along with the freezing points of water and a salt-water mixture, as a reference point for his namesake temperature scale.

This scale was later adopted by scientists in Britain and the Netherlands and is still used today in the United States. With the creation of standardized temperature scales, first by Fahrenheit in 1708 and later by Anders Celsius in the 1740s, scientists could begin to systematically examine the nature of heat. Perhaps unsurprisingly given its importance to early thermometer design, one of the first phenomena examined was body heat. Where people had previously accepted the claims of ancient philosophers that all living organisms simply possessed an "innate heat," an increasing number of scientists now sought to calculate the amount of heat generated within the body, localize its source, and explain its origins. These investigators developed sophisticated instruments that provided quantitative measurements and revealed important links between the physical and life sciences.

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> **Scientists often explore what appear to the public as obscure phenomena that will not impact everyday living. Investigations that are undertaken solely to learn more about the natural world are known as "basic research." While basic research often draws the ire of those concerned about potentially wasteful spending, its impacts can be far-reaching. Basic research 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.**

Quantifying Heat: Joseph Black and the Method of Mixtures

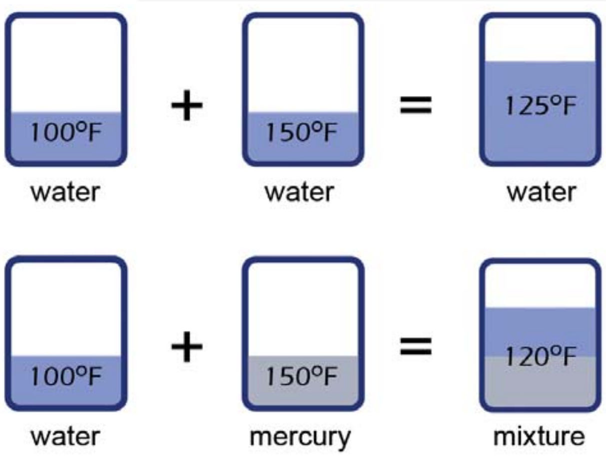
One prominent 18th century scientist with an interest in animal heat was Joseph Black, a professor of medicine and chemistry at the University of Glasgow. Black believed that heat was "inseparably necessary to the very existence of vegetables and animals," and that by understanding its properties he could provide better explanations for various biological phenomena. In 1759, when Black commenced his formal research into the nature of heat, the European scientific community was largely unclear as to what heat was or what a thermometer measured. No distinction existed between the amount of heat contained in a substance and the number obtained by reading a thermometer immersed in it. Within three years, however, the results of Black's research would support the existence of several new phenomena that would dramatically change how scientists wrote, spoke, and thought about heat.

Joseph Black, adapted from engraving by James Heath (Public Domain)

Prevailing knowledge and life experiences impact the way that we see and think about the world. As you read, notice how Black's research profoundly changed scientists' thinking about heat, and this in turn impacted all facets of related research including the tools used, the questions asked, and even what to observe while conducting investigations. As you continue reading, think about how as knowledge changes, the way we see and think about natural phenomena also changes. This, in turn, impacts the questions asked and how research is conducted.

Black based his initial studies on research conducted by Daniel Fahrenheit and the Dutch physician Hermann Boerhaave. Fahrenheit, at the request of Boerhaave, began by combining two equal volumes of water at different temperatures (Figure 1). As might be expected, the resulting temperature of the mixture was exactly halfway between the two initial temperatures. He then altered the investigation by replacing the water in one container with an equal volume of mercury. As Black recounted in a subsequent lecture, 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."

FIGURE 1



Fahrenheit and Boerhaave's investigations concerning the mixture of equal volumes of liquids at unequal temperatures. These early experiments became the basis for a procedure known as the method of mixtures that involved dropping a heated object into an equal mass of water at a lower temperature and using the eventual equilibrium temperature to determine the amount of heat transferred.

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, the results of Boerhaave's experiment contradicted his hypothesis, "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."

1. Scientific investigations are often referred to as "experiments." However, not all investigations are experiments, nor are experiments appropriate for many scientific questions. Entire fields of science such as ecology, geology, and astronomy rely heavily on observational studies, yet produce well-established knowledge. Experiments are studies which manipulate a variable to explore the effect of that change. For example, Fahrenheit and Boerhaave's investigation (Figure 1) was an experiment, because they changed the type of substance being mixed with water to determine its impact on the final temperature of the mixture. As you continue reading, identify an investigation that would be considered an experiment, one that would not be classified as an experiment, and justify your decisions for both.

Boerhaave was at a loss to explain his experimental results. Black, however, was familiar with another experiment conducted by a British Army office, George Martine. Martine had placed the same volumes of mercury and water at equal distances from a large fire and tracked the rate at which each substance's temperature 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."

However, the mercury warmed about twice as fast as the water. Black concluded that the results of Boerhaave and Martine's respective experiments shared a common cause: less heat was required to produce a given temperature rise in mercury than in an equal volume of water. "The quicksilver therefore, may be said to have less capacity for the matter of heat."

In short, Black realized that heat does not distribute itself among bodies in proportion to their density or volume, but based on a characteristic property of each substance, its *heat capacity*. Substances having different heat capacities would thus require different amounts of heat to raise their respective temperatures the same amount.

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Often, passages about science will state that, "the data tell us that…" However, note that Boerhaave was unable to explain the results of his experiment. If data simply told scientists what to think, then researchers would not experience such difficulties, and they would all quickly reach the same conclusions when they did review the results. In reality, nature does not come with labels and definitions. Scientists must use creativity and draw upon their knowledge and experiences to interpret data and put forward ideas that make sense of data. This process explains why scientists can struggle to explain results. As you read further, pay attention to how scientists are working to make sense of data rather than data telling them what to think.

Through the formulation of heat capacity, Black had taken the first step in distinguishing the quantity of heat present in a substance from 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 deduced that the extra heat added to the water could not be detected using a thermometer, because it was converting the liquid into a vapor. The challenge was to somehow determine the magnitude of this otherwise invisible or, in Black's words, "latent" heat.

2. Notice that scientific concepts are not simply buried in nature, waiting for scientists to discover them. As previously noted, scientists must instead use their creativity to develop ideas to help explain the world around them, as Black did here when he developed the concept of latent heat to account for an unexpected phenomenon. This may at first seem like a relatively esoteric point, but its implications are significant. For example, if a person believed that scientific concepts were simply discovered in nature, why do you think they may react with distrust and confusion when they hear about changes to scientific ideas?

To resolve this problem, Black measured the amount of time required to heat up a certain quantity of water from a known starting temperature to its boiling point, as well as how long it took the water to boil away. Using these measurements, Black could calculate the rate at which the temperature increased every minute. Assuming that heat entered the water at a constant rate, he could then determine the temperature the water would have reached during the time it was boiling if it somehow could avoid being turned into steam. Black's calculations revealed that the amount of heat entering the water to transform it into steam would be sufficient to raise the temperature of liquid water by 960°F. Black extended the concept of latent heat to freezing and melting as well, noting that before melting, a piece of ice absorbed enough heat to raise a comparable volume of liquid water's temperature by almost 140°F.

Guinea Pigs and Charcoal: Lavoisier's Calorimeter

While Black developed the concepts of heat capacity and latent heat by 1762, he refrained from publishing his work. Based on surviving lecture notes taken by some of his students, however, he clearly incorporated both ideas in his teaching. In one instance, he used his idea of latent heat to explain how animals could survive high atmospheric temperatures by sweating, noting "that the heat absorbed in spontaneous evaporation greatly contributes to enable [them] to bear the heat of the tropical climates." Black also developed a set of ideas about the origin of animal heat, one of which combined his temperature studies with his research into pneumatic chemistry. In 1727, an English doctor named Stephen Hales had determined that air was not a homogeneous substance but contained many different constituent "airs." Pneumatic chemistry was the investigation of these different gases, and at nearly the same time as he commenced his heat experiments, Black determined that animals taking in atmospheric air breathed out a different substance which he called "fixed air." Later investigations supported the idea that burning charcoal also produced fixed air and that animals died if they were placed in a vessel filled with the gas. He concluded that since warmer animals tend to "infect the air" more strongly, the generation of animal heat was somehow linked to the transformation of atmospheric air into fixed air.

Thanks to his students, Black's ideas on animal heat would spread and inspire further studies of the subject on both sides of the English Channel. One of the most prominent supporters of Black's theories was Adair Crawford, who applied the method of mixtures to compare the specific heats of atmospheric and fixed air. He concluded that atmospheric air had a heat capacity more than sixty times higher than fixed air and that any excess heat contained by the former was released when it was transformed into the latter. Although Crawford was criticized for his inability to support his respiratory theory experimentally and his tendency to present arguments based upon other people's evidence, his work was translated into French in 1781 and found a broad audience among the members of that nation's Academy of Sciences. One member in particular, an ambitious chemist named Antoine Lavoisier, seized upon the concepts expounded in Crawford's work to expand upon his own ideas of heat and combustion.

Lavoisier's approach towards natural philosophy reflected his aristocratic background and his training as a lawyer. The former provided him with the financial resources and leisure time to pursue long-term investigations, while the latter encouraged meticulous note-taking, attention to detail, and an obsession with securing the most accurate measurements possible to support his theories. In 1777, Lavoisier had presented a theory of heat similar to Crawford's which also drew connections between animal respiration and combustion, but he put that work aside in favor of other projects. When news arrived in 1781 that British chemists like Black and Crawford had stolen the lead in the quest to quantify the study of heat, Lavoisier returned to this research, performing the one task which had thus far eluded previous chemists: more directly measuring the amount of heat involved in a chemical reaction.

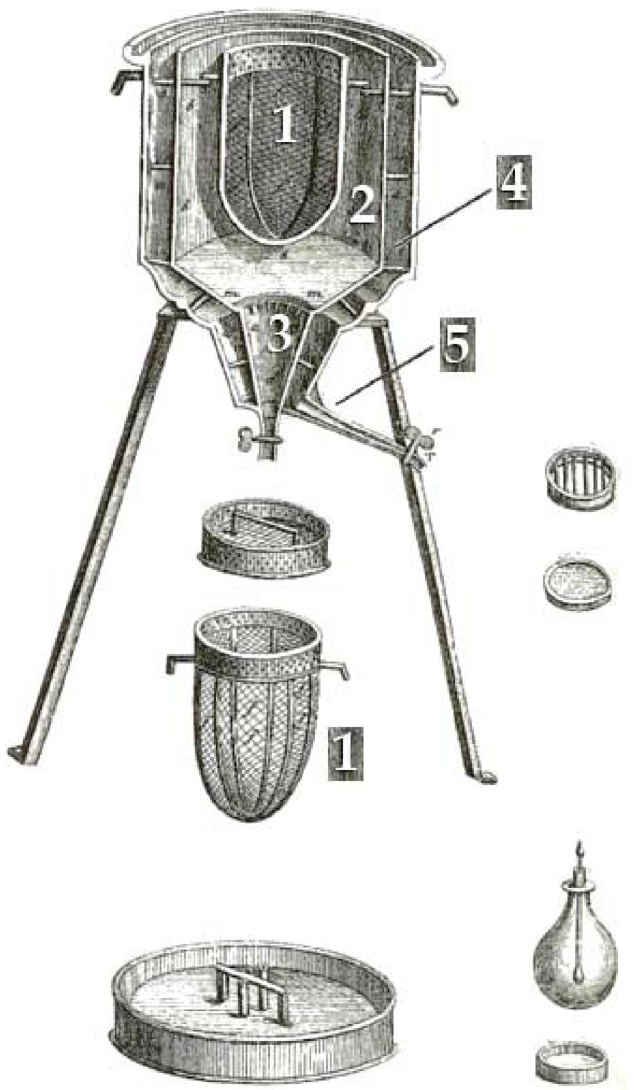

Figure 2. Lavoisier's Calorimeter.
Photo adapted from https://en.wikipedia.org/wiki/Image:Ice-calorimeter.jpg

At his time, scientists calculating the heat capacity of a given substance had to be content with Black's method of mixtures. However, despite its utility, this technique possessed several shortcomings, which most notably includes its unreliable results for substances whose heat capacities were vastly different from water or which took a long time to reach an equilibrium temperature. More significantly, the method of mixtures was intended to provide the heat capacity of a specific substance, so its results were meaningless if the sample underwent a chemical change, as was the case during combustion or respiration. The Swedish physicist Johan Wilcke had attempted to improve the technique by submerging into snow the container in which the substances were mixed, and using the amount of water which melted off as a measure of heat. His results were distorted, however, due to the difficulty of distinguishing between snow melted by the sample under investigation and that which melted due to exposure to the environment.

The solution to Wilcke's problem came from Lavoisier's collaborator, the mathematician and physicist Pierre-Simon Laplace. Laplace suggested that Lavoisier construct a device that also used the amount of ice melted during a chemical reaction to measure the amount of heat released in the process, but unlike Wilcke's experimental setup, effectively isolated the phenomenon under observation from the heat of the external environment. The resulting apparatus, which Lavoisier termed a calorimeter (Figure 2), consisted of a basket with three compartments. The innermost compartment (1) was a wire basket where one placed a specimen. The basket was surrounded with crushed ice and placed into a second chamber (2) which was also filled with ice. As the specimen cooled down, the ice around it melted and the runoff passed through a funnel (3) into a jar where it could be measured. What distinguished this process from Wilcke's earlier investigations was that all of this occurred within a third compartment (4) separating the experimental space from the environment. The ice contained in this outer envelope kept the temperature within the calorimeter constant and any water produced due to the outside heat was collected using its own spigot (5), effectively separating runoff from the investigation and the environment. Therefore, the calorimeter would be able to provide a more accurate measure of heat given off by any substance, even those unsuited for the method of mixtures, without its results being distorted as Wilcke's had been.

Imagine a scientist at work. Many people who respond to this prompt describe a person who is working alone in a laboratory. However, science is rarely a solitary activity, as scientists collaborate on papers, meet in teams to brainstorm ideas, and regularly attend conferences. As you continue reading, note the collaborative nature of the scientific work that is described.

Despite the seeming elegance of Laplace's solution, he and Lavoisier soon learned that the calorimeter experiments required very specific conditions to function effectively. For example, if investigations were conducted on warm days, the cold air from the calorimeter's inner chamber sank down through the funnel only to be replaced with warmer air entering through the top of the apparatus. The increased runoff affected their results so much that the two men decided to postpone their initial work for four months until the weather cooled. In November 1782, they conducted a few simple experiments to confirm the specific heats of mercury, iron, and other common substances. All of this served as preparation for what Lavoisier noted was his ultimate goal: to determine the heat generated by combustion or respiration. "The observation of these phenomena being the most interesting part of the theory of heat," he wrote, "we have thought that a method appropriate to determine these quantities with precision would be of great utility…because without its aid one can form only vague hypotheses about their cause."

In order to study either combustion or respiration, the air within the calorimeter needed to be periodically refreshed, so Lavoisier constructed a second machine with two tubes in the lid allowing atmospheric air to be blown into the inner chamber with a bellows. As before, these studies needed to be conducted at cold temperatures to avoid imparting any extra heat. In January 1783, Lavoisier successfully performed his first combustion investigation with the new equipment, burning a candle and weighing the quantity of ice melted. Soon afterwards, he and Laplace devised a strategy to "establish irrevocably the cause of animal heat." Their plan was to measure the quantities of heat and fixed air an animal produced during a given period of time. They would then compare these findings with the amount of heat and fixed air generated by a piece of burning charcoal to determine whether the heat released during the conversion of vital air to fixed air would account for the heat released by the animal.

On a cold day in February 1783, Lavoisier and Laplace began their investigation by placing a guinea pig inside the calorimeter for approximately six hours. They were able to calculate the heat released by the weight of water melted and collected the fixed air in vials attached to one of the gas tubes on the calorimeter's lid. A few days later, the two men substituted a small glowing piece of charcoal into the device and repeated the procedure, measuring the amount of gas released when the amount of melted ice was the same as that created by the guinea pig. After repeating the investigation several times to confirm their findings, they wrote their results in a *Mémoire sur la Chaleur* (*Memoir on Heat*), concluding that "one can regard the heat which is disengaged in the change of pure air into fixed air by respiration as the principal cause of the conservation of heat of the animal, and if other causes concur to sustain it, their effect is inconsiderable." Where Black and Crawford had simply drawn comparisons between the source of animal heat and chemical combustion, Lavoisier and Laplace went further, claiming that the two processes were fundamentally identical. In each case, the active agent takes vital air, or what Lavoisier would later term "oxygen," from the atmosphere and transforms it into fixed air (later renamed carbon dioxide), releasing heat as a byproduct.

The Body as Machine: New Approaches Toward Respiration

Lavoisier and Laplace's calorimeter investigations suggested that animal heat was not the byproduct of a mysterious inner spark, but rather of chemical processes which could be studied and understood. In this sense, it represented a major step in unifying the physical and life sciences which had previously been considered entirely separate disciplines. This did not mean that the two Frenchmen's findings were immediately accepted by their fellow scientists. Some took issue with their experimental apparatus, noting that even experienced chemists had difficulty using the ice calorimeter to confirm previously determined heat capacity values. Others attacked Lavoisier's claim that respiration was a form of slow combustion which took place inside the lungs, noting that the lungs were not significantly warmer than other parts of the body. Even in 1875, after physiologist Eduard Pflüger confirmed that respiration occurred in tissues spread throughout the body, the nature and source of the materials undergoing chemical reactions in the process remained unclear.

3. Science is often seen as being analogous to solving a very complex puzzle, because the two activities share many traits. For example, just as you assume that a picture puzzle will eventually yield a completed image, scientists must assume that nature is ordered, and things do not just happen at random. Thinking about what you have read about Lavoisier and Laplace's calorimeter investigation, how was their impact on the physical and life sciences similar to solving a puzzle?

One early attempt to resolve the last of these issues came from the laboratory of chemist Justus von Liebig. Lavoisier and his colleagues had previously confirmed that organic compounds consisted primarily of carbon, hydrogen, oxygen, and nitrogen. In 1831, Liebig introduced a set of techniques to accurately determine the percentage of each of these elements in a given substance. He then had his students analyze various foods, and eventually divided foods based upon the relative proportions of carbon to hydrogen and the presence (or absence) of nitrogen, into categories familiar to modern audiences: carbohydrates, fats, and proteins. By the early 1840s, Liebig realized that this provided a potential basis to strengthen the link Lavoisier had forged between chemistry and the life sciences. In 1842, he published *Animal Chemistry*, a book intended to "direct attention to the points of intersection of chemistry and physiology." Liebig claimed that by embracing the methods of contemporary chemists, such as the law of conservation of mass, physiologists could devise an equation relating the inputs and outputs of the respiratory process. Liebig sought to apply this principle to living organisms, using new analytical tools to determine the changes wrought by the body upon food, water, and oxygen. Once the beginnings and endpoints of this process were established, Liebig argued that it would be possible to deduce "phenomena invisible to bodily sight," the intermediate processes of chemical transformation which occurred within the body.

While Liebig would eventually admit that he had been overly optimistic about the prospects of determining the chemical reactions underlying respiration, he held firm to his idea that different bodily functions were associated with the various categories of foodstuffs. For instance, he proposed that the energy for motion came from protein that was consumed in muscles. Although Liebig implied that chemicals in the body could be transformed into motion, he was vague about the interconversion process. The deficiencies of what one critic called this "shopkeeper's bookkeeping" prompted an aspiring physiologist named Hermann von Helmholtz to reexamine Liebig's claims about the muscle function. Helmholtz's work supported the notion that mechanical, electrical, thermal, and chemical processes were all intertwined, prompting him to publish an essay "On the Conservation of Force" in 1847. This paper, along with the recent calculation of a mechanical equivalent of heat by Julius Mayer and James Joule, elaborated a new concept which would ultimately serve to undermine Liebig's ideas regarding respiration: the conservation of energy.

The final blow came in 1866 when a pair of physiologists, Adolf Fick and Johannes Wislicenus measured the levels of protein byproducts in their blood before and after climbing a mountain in the Bavarian Alps. They used this information to calculate the energy available in the protein which Liebig argued would be consumed by the climb and determined that it was far less than the estimated amount of energy necessary to make the trip. Their data were further refined by British chemist Edward Frankland, who determined that Liebig's calculations accounted for less than half the total work performed during the climb. Muscle fiber alone could not serve as the source of mechanical energy.

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Lavoisier and Laplace made significant advances in science, yet their ideas were not readily accepted and both put forward ideas that were rejected. Extensive time and effort are required to develop and establish ideas that make sense of natural phenomena, and a strength of science is that ideas, no matter how well supported, are open to revision in light of new evidence or reinterpretation of already existing evidence. However, scientists have good reasons to be generally skeptical of work that goes against prevailing knowledge, particularly if that work calls for major changes in well-established knowledge. If scientists easily changed their minds in response to every new study, then their fields would be in constant turmoil.

Measuring Energy: Calorimetry Comes into its Own

The use of thermodynamic ideas like work and energy may have thwarted Liebig's efforts to explain the elementary chemical balance in animals, but it also provided a new generation of European physiologists with a new lens through which to view questions of respiration and metabolism. These scientists, working in France, Germany, and Britain, continued to work into the 20th century to refine Lavoisier's calorimeter in order to more effectively measure body heat.

Between 1889 and 1894, Max Rubner utilized his new experimental calorimeter setup in a series of investigations intended to support the idea that the conservation of energy, which in previous physiological studies had been either assumed or loosely tested, applied to biological systems. To achieve this goal, Rubner tested "whether the substances burned in the body possess the same quantity of heat as was given off by the surface of the animal body." He placed several dogs of various sizes in his respiratory calorimeter and measured their heat output. Over time, he varied their diets and recorded any subsequent changes in their body heat or respiratory output. By the end of his experiments, Rubner wrote, "[n]ot a single isolated datum chosen at will out of all these experimental results can leave us in any doubt that the exclusive source of heat in warm-blooded animals is to be sought in the liberation of forces from the energy supply of the nutritive materials."

Through his meticulous application of calorimetry, Rubner revealed that the gas exchanges and protein degradation which Lavoisier and Liebig had respectively cited as sources of animal heat were themselves byproducts of a more complex chemical process which transformed food into energy. As Helmholtz and the other founders of thermodynamics had suspected, even the simplest organisms could be viewed as heat-generating machines, subject to the principle that while energy might change forms, it is always conserved. Even though the intermediate metabolic processes which eluded Liebig would not be clarified until the following century, Rubner and his fellow physiologists had shown that there was no need for a separate "vital force" to explain the origins of the "blood heat" which had mystified earlier philosophers. Using complicated tools and meticulous, sometimes indirect, methods, it was now clear that the physical and life sciences operated according to the same fundamental laws.

4. The first bullet point in this story noted that basic research creates a broad base of knowledge upon which other scientists can make connections that would otherwise be impossible, and often results in the creation of technology that profoundly changes the world. Draw from this story or some other example of basic research, and show how that research resulted in technology that has significantly impacted society.

Epilogue: Counting Calories

Although Rubner remains a relatively obscure figure in the history of respiratory physiology, he deserves credit for popularizing a unit of heat which most people today take for granted: the calorie. The term itself was already well-known in Europe, having first been coined by a French engineer named Nicholas Clément. In 1824, Clément defined the calorie as the amount of heat needed to raise the temperature of a kilogram of water by one degree Celsius. Previous scientists like Black and Lavoisier had used various alternative units. Lavoisier, for example, never used the calorie in his work, preferring instead to measure the amount of heat needed to raise the temperature of a *livre* (approximately a pound) of water. Even after Clément popularized the term, scientists resisted using the calorie in their work. James Joule, the British engineer whose surname would later become the metric unit of work and energy, avoided the term until 1878; his description of the mechanical equivalent of heat used British Thermal Units, referring to the amount of heat required to raise a pound of water by one degree Fahrenheit.

However, by the end of the 19th century, the calorie had become the preferred unit of heat among both engineers and physiologists, though it had gradually evolved into two distinct forms. Some, like Julius Mayer, adopted Clément's original definition of the calorie (later known as the Calorie kg-cal) while others like Edward Frankland embraced another unit equal to the amount of heat needed to raise the temperature of one gram of water by one degree Celsius. This later unit, known as the calorie or g-cal, was used by scientists at the University of Munich, including Carl Voit and Rubner. By 1885, Rubner had published papers using the g-calorie to define heats of combustion for food and energy released during respiration studies.

One visitor to Voit and Rubner's laboratory in Munich was an American agricultural chemist named Wilbur Atwater. Atwater pursued postdoctoral studies with the two men, who taught him how to use a respiratory calorimeter and introduced him to both types of calorie. When Atwater returned to the United States, he became interested in determining the nutritional value of foods and started giving public lectures on the economic importance of buying foods with high protein and energy content. In 1887, he published a series of articles in *Century* magazine defining the Calorie (i.e., kg-cal) for American audiences. Soon afterwards, Atwater was offered a position as director of an agricultural experiment station in Connecticut, where he set to work compiling a database of the amount of energy in different foods using Rubner's calorimetry methods.

Early in the 20th century, the Department of Agriculture published Atwater's work in a *Farmers' Bulletins* series which served as the foundation for a modern science of diet and nutrition. By 1918, Lulu Hunt Peters had incorporated Atwater's research into a new book, *Diet and Health with Key to the Calories,* which was meant to assist Americans' efforts to eat healthy foods and avoid becoming overweight. Although the metric system officially adopted the joule (defined as one Newton-meter worth of work) as its official unit of heat that same year, the Calorie remained the unit of choice among Americans tracking the amount of energy in their food. As recently as 1970, the Committee on Nomenclature of the American Institute of Nutrition officially advised that the calorie should be replaced in scientific publications with the kilojoule. As of yet, however, the calorie remains entrenched both in journals and on food packages, a quiet reminder of the efforts of chemists, physicists, and physiologists who sought over the course of two centuries to link physical and biological systems and the origins of animal heat.

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