CONSERVATION OF ENERGY:

HOW WE CAME TO KNOW THAT HEAT WAS MOTION

In the 18th century energy was called "*vis viva"*, the living force, and was thought of as what made the universe work. It's most obvious characteristic was making things move: stars, planets, people, horses, clouds, you name it. If it moved, it was endowed with *vis viva*. Heat, on the other hand, was seen as an entirly different creature. The prevailing view held that heat was something totally separate from *vis viva*. It was an invisible fluid, named "caloric."

It was in 1712 that relating heat to energy became urgent for it was then that Thomas Newcomen invented the steam engine. Originally designed to pump water from mines, the steam engine was nothing more than a machine for harnessing energy, which is just what we needed to get the industrial revolution underway. And this is why heat became important, the hotter a steam engine runs, the more work it can do, and hence, the more money there is to be made. Throughout the remainder of the 18th century, people like James Watt and Richard Trevithick labored to improve steam engines by making them do more work and hence make more money.

As heat is typically the result of burning something, and burning was the province of the new science of chemistry, it seemed natural that chemists should be the ones to explain heat. This was regrettable, for unlike physics where we talk about mass, force and velocity as concepts independent from the existence of real things, chemistry is about tangible elements and compounds. And so, it is not surprising that chemists should impress upon heat a physical form. In his seminal 1789 text *An Elementary Treatise on Chemistry*, Lavoisier begins his list of the thirty-three "known" elements with caloric, followed by light, then oxygen, nitrogen, and hydrogen. Two decades later, the Swedish chemist Jöns Jakob Berzelius classified caloric as one of five invisible and weightless substances, along with positive and negative electricity, light and magnetism.

Like its presumed vaporous counterpart static electricity, caloric was pictured as self-repulsive, a property that was believed to explain why *everything* expands on warming. (This generalization is not entirely correct. Rubber, for example, contracts as temperature increases. Over a temperature range of a few degrees, so do water and plutonium.) Heating a thing was supposed to increase its concentration of this repulsive fluid, which should then force its substance farther apart. While not particularly dramatic in solids, where the expansion is small, it is quite noticeable in a gas, like steam, where the volume change can be used to pump water or turn a gear. Frictional heating, e.g. rubbing your hands together to warm them on a cold day, was neatly rationalized by assuming some caloric was "squeezed out" by contact, warming the surrounding area.

The flaw in the caloric theory of heat surfaced in a cannon factory in 1797. Count Rumford, born Benjamin Thompson, was the Commandant of Police at the court of Carl Theodor, Duke of Bavaria, and was responsible for the defense of Munich. Thompson had an early interest in heat, fire, and energy. As a thirteen-year-old living in his family home outside of Boston, he kept orderly notes for the construction of rockets and other fireworks. An unexpected explosion while assembling fireworks severely burned Thompson, but did not prevent him from pursuing his passion for heat. Thompson is credited with the invention of the double boiler, the kitchen range, and the "Rumford stove." This latter invention brought him fame and fortune as it yielded more heat per pound of wood and eliminated smoke from the living space through an exhaust flue.

In 1775, having married a wealthy widow nineteen years his senior, Thompson settled in Concord, New Hampshire (previously called Rumford, New Hampshire). A Tory, he spied for the royal authorities, passing notes written in another of his inventions, secret ink. He was arrested once, then released for lack of sufficient evidence. By 1776, the British presence in Boston was unsustainable and Rumford fled to Munich, abandoning his wife and their infant daughter.

The city he was charged with defending stood directly between the republican forces of the French Revolution and their enemy, the Hapsburgs of Austria. Though Bavaria was neutral in this conflict, Rumford ordered and oversaw the manufacture of heavy brass cannons, to protect the city.

Cannons were first cast solid, and then the barrel was bored with a stationary hardened steel drill bit held with great force against the cannon as it was rotated. The power for the process was provided by draft animals and transmitted to the cannon by a series of gears and pulleys. The frictional heating of the steel drill bit, in particular, would have been tremendous, causing it to glow ever so slightly in the dim light of the factory. This may have prompted Rumford to wonder how much heat—how much caloric—was in a cannon.

In no time at all, he set about measuring the heat liberated when metal rubbed upon metal. He cast a specially shaped insulated cannon barrel, replacing the sharp bit with a dull one, then immersed the whole thing in a tank of water to collect the heat released. As he wrote later,“ … I perceived, by putting my hand into the water and touching the outside of the cylinder, that Heat was generated; and it was not long before the water which surrounded the cylinder began to be sensibly warm.” He goes on to write "… at two hours and thirty minutes it *actually boiled*. It would be difficult to describe the surprise and astonishment expressed in the countenances of the bystanders, on seeing so large a quantity of cold water heated, and made to boil, without any fire."

As might be expected of the inventor of the kitchen range, Rumford's imagination immediately turned to the practical: "…[with] such a large quantity of Heat … produced …by the strength of a horse, without either fire, light, combustion, or chemical decomposition; and in the case of necessity, the Heat thus produced might be used in cooking victuals." Instantly tempered by scientific intuition, Rumford then notes that burning the horse's fodder might produce more heat and with far less bother, linking the drill's heat to the horse's digested oats and auguring the discovery of energy conservation fifty years later.

Toward the end of the experimental discussion, the Count returns to his primary interest: "By meditating on [these] results, we are naturally brought to that great question which has so often been the subject of speculation among philosophers; namely: What is Heat? Is there anything that can with propriety be called *caloric*?"

He concludes in the negative, arguing the illogic that brass should contain an apparently unlimited amount of such a substance, lest the cannon barrel melt of its own accord. With characteristic brilliance, he reasons, "It is hardly necessary to add that anything which any *insulated body* …can continue to furnish *without limitation* cannot possibly be a *material substance*; and it appears to me to be extremely difficult, if not quite impossible, to form any distinct idea of anything capable of being excited and communicated in a manner that Heat was excited and communicated in these experiments, except it be *Motion*."

Count Rumford's reasoning should have left the caloric theory in much the same state as its originator and chief proponent Lavoisier, who was guillotined in 1794 upon false accusations of corruption by fanatics of the French Revolution. But it did not. Rumford refused to even speculate on what it was that moved when heated. "I am very far from pretending to know how…that particular kind of motion in bodies which has been supposed to constitute heat is excited, continued, and propagated…[And] I shall not presume to trouble the [reader] with mere conjecture." The failure to provide a mechanistic theory for heat and its transport doomed Rumford's theory to obscurity, where it would remain for more than twenty-five years until discovered anew, dusted off, and finally recognized as the foundation of the new science christened *thermodynamics*. A small triumph for the Count: "thermo" comes from the Greek for "heat," and "dynamics" is the study of motion. Heat is movement and thus, energy.

By the middle of the 19th century, many, though not all, scientists knew of Rumford's cannon experiment and accepted this interpretation. Yet, two questions remained. The first was the continuing concern over what exactly it was that moved in a heated object—the question Rumford wouldn't touch. Today we know that moving atoms and molecules "constitute" and "propagate" heat. But this realization comes nearly one hundred years after the war for the atom was fought. For the chemists and physicists of the early 19th century, the battle lines had yet to be drawn. Atoms were, at best, heuristics, devoid of physical reality but useful for justifying the fact that elements combine in constant proportions. Connecting motion with heat added to the growing data, pointing to the existence of physical atoms. As the investigation of heat continued, the evidence would become overwhelming.

While the first question went unanswered, several scientists were determined to answer the second question: How much movement produces how much heat? James Prescott Joule did it best.

Joule was a gifted and dedicated experimentalist, obsessed with finding the mechanical equivalent of heat. The supposed extent of his obsession is described in a story, originally told by his friend William Thomson, Lord Kelvin. As the story goes, Thomson was vacationing near Mount Blanc on the French-Swiss border during the summer of 1847, when, during a walk, he chanced upon the honeymooning Joule and his new bride. Thomson was surprised to see Joule carrying a thermometer. On enquiring as to its purpose, Joule explained his intention to measure the temperature increase resulting from water descending a fall, a necessary increase if energy is conserved. So dedicated was Joule that he could not pass up an opportunity to work—even on his honeymoon.

The water at the bottom of a fall *is* warmer than at the top, and the greater its height, the greater the temperature difference. But even in a very high fall, the temperature difference is a small one. So, apocryphal or not, the story captures the essence of the task confronting Joule: He had to determine the mechanical equivalent of heat by showing that a given amount of energy always produces the same amount of heat. And to do so, he had to make *very* precise measurements.

Joule was up to the task. With constant practice, he had learned to read a thermometer within 1/200 of a degree Fahrenheit, a skill William Thomson called "magical." In addition, he employed two different techniques in order to bypass objections that results were subjective and dependent on details of the experiment.

In his first approach, Joule used electricity to produce heat. At the age of 22, he had discovered that an operating electric circuit produces a predictable amount of heat, which depends only on the current and resistance of the circuit and the length of time it operates. In addition, he knew that a dynamo—a coil of wire that rotates in a magnetic field—could be driven by a slowly falling weight to produce a constant current. If the circuit were placed in an insulated container filled with water, the heat would go to raising the temperature of the water, which he could then measure with a thermometer. Joule reasoned that if energy were conserved, the potential energy lost by the falling weight would appear as heat, thus warming the water.

Joule found that a 772-pound weight slowly falling through one foot, or a one-pound weight slowly falling through 772 feet (or any combination in which the product of the weight with the distance fallen is equal to 772 foot X pounds) raises the temperature of one pound of water 1^{o} F.

In his second experiment, Joule eliminated the dynamo. Instead of turning a coil of wire, the falling weight turned a submerged paddle wheel. After all, it didn't matter what forms energy went through while turning into heat, it was conserved. As expected, he found the same relationship: 772 foot X pounds of energy provide the heat necessary to raise the temperature of one pound of water 1^{o} F. This amount of energy we now call the British Thermal Unit, or BTU.

This high cost—a lot of energy to produce a little heat—explains why the conservation of energy was not discovered sooner. The temperature of those apples falling from Newton's tree would have increased by a few hundredths of a degree Fahrenheit. If we had senses like pit vipers (rattlesnakes, copperheads), the conversion of kinetic energy to heat would be readily apparent. A pit viper "sees" heat and can discern tiny differences in temperature. To rattlers, an apple would visibly warm when hitting the ground. But alas, we have no such sense and had to wait for Joule and his magical skills with a thermometer to discover this most fundamental law of nature.

In recognition of Joule's accomplishment, the unit of energy in the metric system was named the "Joule." One Joule is equal to roughly one thousandth of a BTU. The kinetic energy of a two-kilogram mass (2.2 lbs) traveling at one meter per second is equivalent to a Joule. Another way to look at it: there are 1463 kilojoules (1000 Joules) in a 'good' candy bar (whereby 'good' I mean a loaded 350-calorie chunk of chocolate). Joule had succeeded in illustrating that with the energy in such a bar, the body temperature of a 165-pound individual could be increased by approximately 8.4^{o} F. Or that same energy could lift that same person 1.25 miles into the air, or propel him or her through a vacuum to a velocity of 440 mph. Since energy is conserved, this also works the other way around. To remove the energy of that single 'good' candy bar, you would need to climb a 1.25 mile mountain, run very fast, or somehow raise your body temperature to dangerously high levels.

A few years following Joule's experiments with heat, the conservation of energy was ensconced as a basic principle of physics. Reformulated in a mathematical form by the great theoretical physicist Hermann von Helmholtz, it became the First Law of Thermodynamics. There would be one more significant and totally unexpected addendum to the First Law in 1905, when, over a period of fifteen weeks, a young patent clerk published three papers that would revolutionize physics. That clerk, of course, was Albert Einstein.

Two of the three extraordinary papers provided insight into the First Law. The first confirmed that atoms and molecules communicate and propagate heat. The confirmation came as Einstein was able to explain why smoke particles in air exhibited random and jerky motion. He showed this to be the result of collisions between the smoke and much smaller moving particles. Though it came hundreds of years too late for Rumford, it was the final piece of evidence needed to convince many scientists of the existence of atoms and molecules.

No one had anticipated the conclusions that could be drawn from the second paper. Einstein indicated that mass was just another form of potential energy. The famous equation $E = mC^2$ (energy is equal to mass times the speed of light squared) shows that just as heat is equivalent to energy, so too, is mass.[1] With this expanded insight, the full statement of the First Law requires that mass/energy be conserved. The universe is composed of nothing but energy packed together in various ways; everything that we observe involves energy converting between its several forms—kinetic, potential, heat, or mass—while its total amount remains the same.

[1] *This means that a the total energy content of a one kilogram mass is equivalent to that of more than 61-billion good candy bars*