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Prologue

Thermodynamics is a dreadful name for what is arguably the most useful and universal scientific theory ever conceived.

The word suggests a narrow discipline concerned only with the behavior of heat. Here indeed lie the subject's origins. But it's grown far beyond that and is now more broadly a means of making sense of our universe.

At its heart are three concepts—energy, entropy, and temperature. Without an understanding of these and the laws they obey, all science—physics, chemistry, and biology—would be incoherent. The laws of thermodynamics govern everything from the behavior of atoms to that of living cells, from the engines that power our world to the black hole at the center of our galaxy. Thermodynamics explains why we must eat and breathe, how the lights come on, and how the universe will end.

Thermodynamics is the field of knowledge on which the modern world is based. In the years since its discovery, we have seen the greatest improvement in the human condition in the history of our species. We live longer, healthier lives than ever before. Most children born today are likely to reach adulthood. Though much remains wrong with our time, few of us would swap places with our ancestors. Thermodynamics alone didn't cause this, but it was essential for it to happen. From sewage pumps to jet engines, from a reliable electricity supply to the biochemistry of lifesaving drugs, all the technology that we take for granted needs an understanding of energy, temperature, and entropy.

Yet despite its importance, thermodynamics is the Cinderella of the sciences. The subject is introduced piecemeal in secondary school physics, and the concept of entropy, so vital to our understanding of the universe, is barely mentioned.

I first encountered the study of thermodynamics in the second year toward my undergraduate engineering degree at Cambridge University, where it was presented as relevant only to car engines, steam turbines, and refrigerators. If instead I had been told that it provided a unified and coherent way of understanding all science, I might have paid more attention. Most adults are similarly introduced to the topic; even ones who consider themselves educated are ignorant of humanity's greatest intellectual achievement in the sciences. We count calories, pay energy bills, worry about the temperature of the planet, without appreciating the principles underpinning those actions.

The Cinderella status of thermodynamics is reflected in the way Einstein's science is remembered. All acknowledge his immense and revolutionary contributions, yet few realize the extent to which his work derived from thermodynamics or that he made seminal contributions to the subject. In his so-called miracle year of 1905, he published four papers that transformed physics, including the one featuring the equation $E = mc^2$. This work did not emerge from nowhere. For in the previous three years, Einstein had published three papers on thermodynamics, and the first two of the miracle-year papers—one on the atomic structure of matter and the other on the quantum nature of light—were continuations of that work. The third miracle-year paper, on special relativity, took an approach to physics inspired by thermodynamics, and the fourth, in which he derived $E = mc^2$, united the Newtonian concept of mass with the thermodynamic concept of energy.

Of thermodynamics Einstein said, "It is the only physical theory of universal content, which I am convinced . . . will never be overthrown."

Nor was Einstein's interest in thermodynamics limited to its role in fundamental and theoretical physics. He cared about its practical applications, too. In the late 1920s, he worked on designing cheaper and safer refrigerators than those available at the time. This little-known episode was not a quirky sideline, for he worked for several years on the project and successfully raised funding for it from the engineering companies AEG and Electrolux. The direct motivation for Einstein's interest in refrigerator design was that, in 1926, he read an article in a Berlin newspaper about a family—which included several children—who died because their malfunctioning refrigerator had leaked lethal fumes. Einstein's response was to initiate a project to design safer refrigerators.

Thermodynamics isn't just great science; it's great history, too.

• • •

In early 2012, while producing a television documentary, I came across *Reflections on the Motive Power of Fire*, a slim book self-published in Paris in 1824 by a reclusive young Frenchman called Sadi Carnot.

Carnot had died of cholera at thirty-six, believing that his work would be forgotten. Yet within two decades of his death, he was considered the founding father of the science of thermodynamics. Later in the nineteenth century, the great physicist Lord Kelvin said of Carnot's text, "that little essay was indeed an epoch-making gift to science."

I also became captivated. Carnot's work was unlike any other work of fundamental physics, combining algebraic calculus and physical insight with Carnot's thoughts on what would constitute a happier, fairer society. Caring deeply for humanity, Carnot believed science was the key to progress.

Carnot's science was also a response to the seismic social changes in early nineteenth-century Europe. In that sense, *Reflections* was as much the product of two revolutions—the French and the Industrial—as it was of Carnot's brilliant mind. As I then started to read more about the scientists who picked up the baton from him, I saw how all their work was influenced by events in the world around them. The story of thermodynamics is not only one about how humans acquire scientific knowledge, it is also about how that knowledge is shaped by and, in turn, shapes society.

This book is an argument that the history of science is the history that matters. The men and women who push back the frontiers of knowledge are more important than generals and monarchs. In the following pages, I shall therefore celebrate the heroes and heroines of science and show their quest to discover the truth about the universe as the ultimate creative endeavor. Sadi Carnot, William Thomson (Lord Kelvin), James Joule, Hermann von Helmholtz, Rudolf Clausius, James Clerk Maxwell, Ludwig Boltzmann, Albert Einstein, Emmy Noether, Claude Shannon, Alan Turing, Jacob Bekenstein, and Stephen Hawking are among the smartest humans who ever lived. To tell their story is a way for all of us to comprehend and appreciate one of the greatest achievements of the human intellect.

Ludwig Boltzmann, one of the heroes of this story, put it this way:

"It must be splendid to command millions of people in great national ventures, to lead a hundred thousand to victory in battle. But it seems to me greater still to discover fundamental truths in a very modest room with very modest means—truths that will still be foundations of human knowledge when the memory of these battles is painstakingly preserved only in the archives of the historian."

Steam power in early nineteenth-century Britain was ubiquitous but not as innovative as Say thought. The technology had proliferated not because Britons were especially inventive, but because their country was so replete with coal that even poorly designed and wasteful engines were profitable. Take, for example, the one installed at the Caprington Colliery in southwest Scotland in 1811, which operated on a principle pioneered a century earlier by an English inventor called Thomas Newcomen. Devices such as this weren't what we, in the twenty-first century, regard as steam engines, in which the pressure exerted by hot steam pushes a piston. Instead, they are best understood as steam-enabled vacuum engines. The relationship between the heat created in their furnaces and the mechanical work they perform is convoluted and inefficient.

A Newcomen engine

"Newcomen engines" work as follows: Heat from burning coal creates steam. This flows via an inlet valve into a large cylinder in which a piston can move up and down. Initially the piston rests at the top of the cylinder. Once this is full of steam, the inlet valve closes. Cold water is sprayed into the cylinder, cooling the steam inside, causing it to condense into water. Because water occupies much less space than steam, this creates a partial vacuum below the piston. Atmospheric air will always try to fill a void, and the only way it can do so in this arrangement is by pushing the piston down. This is the source of the engine's power. The steam is a means to create a vacuum and the downward pressure of the atmosphere does the work.

To observe this effect, pour a small amount of water into an empty soft-drink can and warm it until it's filled with steam. Take some safety precautions and pick up the can with tongs—it will be hot—and quickly turn it upside down as you submerge it in a bowl of ice-cold water. The steam condenses into water, thus creating a partial vacuum inside the can. Pressure from the earth's atmosphere will then crush the can.

In the steam engine I've been describing, this process—filling the cylinder with steam and condensing it to water so a partial vacuum is created—repeats over and over. Thus, the piston goes up and down, powering a pump.

Newcomen engines consumed prodigious amounts of coal. They burned a bushel—84 pounds—of coal to raise between 5 to 10 million pounds of water by one foot. This quantity, the amount of water that can be raised by one foot for every bushel burned, was called the engine's *duty*. By modern standards, these engines were very inefficient, wasting around 99.5 percent of the heat energy released as the coal burned.

That such wasteful engines continued to be used for over a century was due to cheap coal. At the time of Say's visit, Britain's mines produced 16 million tons every year, and in the new industrial towns of Leeds and Birmingham, coal often sold at less than ten shillings per ton. At these prices, poor engine design mattered little.

Then in 1769, the Scottish engineer James Watt had patented a modification to the Newcomen engine, which roughly quadrupled its duty. But the arrival of Watt's designs, paradoxically, put a brake on British innovation for thirty years as he and his business partner Matthew Boulton used the patent system to prevent other engineers from bringing further improvements to the market. Then, as now, commercial success was not necessarily aligned with innovation.

In addition, the people of England had a love-hate relationship with science. On the one hand, over the eighteenth century, the country's growing middle class had developed a great interest in natural philosophy, as science was termed. Encyclopedias were bestsellers. Crowds flocked to public lectures that covered topics from the behavior of magnets to recent astronomical discoveries. Clubs sprang up as informal gatherings for scientific discussion. The most famous came to be known as the Lunar Society, which counted Watt and Boulton as members. But on the other hand, some sections of the public also grew wary of science because many of its practitioners, such as Joseph Priestley, the discoverer of oxygen, publicly supported the radical politics of the French Revolution. He paid dearly for his views. In 1791, an angry mob burned down his house and laboratory.

Moreover, England's two universities, Oxford and Cambridge, offered no courses in subjects that resemble modern-day physics and engineering. Cambridge, being Isaac Newton's alma mater, did rigorously train students in the mathematical principles that great scientist had discovered. But basking in Newton's legacy, professors there saw no need to extend his work and were suspicious of novel mathematical techniques being developed abroad. In 1806, when one progressive scholar, Robert Woodhouse, urged the adoption of a European style of mathematics, he was condemned as unpatriotic in the conservative *Anti-Jacobin Review*. The real-world applications of mathematics were also not a priority. Yes, Newton's laws did describe aspects of the universe we inhabit such as the orbits of planets. But Cambridge professors felt the purpose of teaching the laws was to provide mental training to students drawn from the landed gentry who would go on to serve church, state, and empire. Cambridge students railed against this, but it would be decades before attitudes changed.

France, however, was very different.

Jean-Baptiste Say published his observations on Britain's economic and industrial transformation in a book entitled *De l'Angleterre et des Anglais*, in 1816. His report, and those of others, convinced French engineers, businessmen, and politicians that the way to catch up with Britain economically was to exploit steam power. But they faced a problem: coal was scarce south of the Channel. French mines produced a million tons annually, and as most of these were in the remote Languedoc region, the price never dropped below twenty-eight shillings per ton, three times higher than in

England's industrial heartland. This meant that from the earliest stages of their country's industrialization, French engineers cared about engine efficiency—how to maximize the useful work that can be extracted from burning a given amount of coal—in a way most of their British counterparts did not.

French scientific and mathematical education was also very different from that in Britain, as is exemplified by the institution where Say became professor of industrial economy three years after returning to his homeland. The National Conservatory of Arts and Crafts, as it was named, was a far cry from an elite institution such as Cambridge. Located in Paris, the Conservatory was created as part of the French revolutionary government's commitment to public education, and it embodied that regime's conviction that science and mathematics were weapons in a war against superstition and arbitrary aristocratic privilege. They provided rational laws to help found a rational society. Subsequently, Napoléon continued to support these subjects, seeing them as important to France's military ambitions. Working in this context, French scientists, therefore, saw Newton's work as a foundation on which to build. They widened its reach and made it far simpler to use. At places such as the Conservatory, it was natural to think that mathematical analysis could be applied to steam engines and, in particular, to their efficiency.

And here a young student laid the foundations of the science of thermodynamics.

CHAPTER TWO

The Motive Power of Fire

> It is necessary that there should also be cold; without it, the heat would be useless.
>
> —Sadi Carnot

> The young man is extremely gentle, he behaves well and is a little shy. . . . His confidence must not be undermined.
>
> —A friend's description of Sadi Carnot

Still in his twenties, of medium build and possessing a "delicate constitution," Sadi Carnot was reserved and introspective and lived a solitary life. Fellow students at the Conservatory of Arts and Crafts in Paris in the early 1820s paid him little heed. A surviving portrait pictures him as cultured, thoughtful, and yet somehow fragile in appearance.

Sadi Carnot was born on June 1, 1796, in a room in the Palace of the Petit Luxembourg in Paris. His father, Lazare, was a gifted mathematician and engineer, who as a young man had published a paper suggesting ways of improving the Montgolfier brothers' famous hot-air balloon of 1783. Lazare's other scientific essays included investigations into the principles underpinning machines such as water mills. Lazare was also an admirer of a thirteenth-century Persian poet, Saadi of Shiraz, hence the unusual first name he had given his son.

In 1789, when the French Revolution began, Lazare turned to politics, and two years later, he won election as a deputy to the country's quasi-democratic Legislative Assembly. He then rose to prominence thanks to his highly effective reorganization of the French Revolutionary Army.

more caloric was needed to cause a given temperature increase. Caloric didn't only make things hotter—it could cause them to melt or boil. Many scientists regarded caloric as a gaseous element like oxygen, which could flow from one place to another. And just as elements such as oxygen could not be created or destroyed, neither could caloric.

By the early 1800s, however, many scientists grew aware of weaknesses in caloric theory. One such was an American émigré scientist based in Munich named Benjamin Thompson, working as aide-de-camp to the ruler of Bavaria. His duties included overseeing the national arsenal, and he observed that when cannon barrels were hollowed out by a tool resembling a giant drill bit, the friction generated an enormous amount of heat. To investigate further, Thompson immersed a cannon barrel in water while it was being drilled. After two and half hours, so much heat was generated that the water began to boil.

In a paper submitted to Britain's leading scientific body, the Royal Society, Thompson argued that though caloric theory could explain why heat was released from burning, it couldn't explain why it was released by friction. In the former process, it was plausible that trapped caloric particles escaped as fuel burned. Once the fuel was used up, caloric was no longer released. Friction, on the other hand, appeared to be a limitless source of heat. As long as mechanical effort was spent rubbing two objects together, heat would emerge. In other words, friction seemed to *create* heat, not release it. This went against the assertion in caloric theory that heat could neither be created nor destroyed. (Thompson, arch-critic of caloric theory, married Marie-Anne Lavoisier, widow of one of the theory's founders, the famous French chemist Antoine Lavoisier, who had been executed during the Terror. Thompson and Mme Lavoisier's marriage was short.)

In addition to the strengths and weaknesses of caloric theory, Carnot learned Clément's own contribution to the study of heat, namely that he had devised an objective way of quantifying it. Prior to Clément, despite people's building steam engines for over a century, there was no universally agreed unit for measuring amounts of heat. Cornish mining engineers had come up with the concept of an engine's "duty"—the weight of water in pounds raised by one foot when a bushel, or eighty-four pounds, of coal was burned in its furnace. But they hadn't thought to quantify the heat given off by the coal as it burned. People also knew, for instance, that it took more heat to boil a liter of water than it took to boil a liter of alcohol, but there was no agreed way to compare the different amounts of heat numerically. Clément came up with a method for doing so.

We know all this from an anonymous account of Clément's lectures that survives. In them are the historic words "Mr. Clément imagines a unit of heat that he names the 'calorie.' One calorie is the amount of heat needed to elevate by one degree centigrade one kilogram of water." That is still what a calorie means when used to measure the energy content of food. So for example, a hundred-gram packet of potato crisps that contains around five hundred calories, per Clément's definition, will release enough heat on burning to raise the temperature of five hundred kilograms of water by one degree Celsius. (A few decades later, scientists redefined the calorie to mean the amount of heat needed to raise the temperature of one gram of water, rather than one kilogram of water, by one degree Celsius, which means that one of Clément's calories is equivalent to one thousand calories now.)

Another influence on Carnot was his father Lazare's scientific papers, written in the decade before the revolution. In one entitled "An Essay on Machines in General," Lazare had mathematically analyzed the behavior of water mills.

Specifically, Lazare imagined an *ideal* mill in which all the "pushing power" of the water is turned into the rotary motion of the wheel and none is wasted. In such a mill, the water slows gradually as it turns the wheel, transferring all its speed of flow to the wheel's rotational movement. Lazare observed that real mills fell far short of this ideal, but he offered meager advice on how to remedy this. He focused, instead, on the physics underpinning waterpower with the aid of mathematics. Unsurprisingly mill builders paid little attention to Lazare's abstract form of reasoning, but his son would use this approach to great scientific effect.

In 1821, Carnot traveled to Magdeburg to visit his exiled father and younger brother for a few weeks. The timing was propitious. The city's first steam engine had been installed three years earlier by an expatriate English engineer—such men built a large proportion of the few engines in continental Europe at this time. It's not a stretch to speculate that Lazare and Sadi visited the engine and noted how the British led the world in steam technology. In any event, when Sadi Carnot returned to Paris, he set to work immediately on a seminal text. When he completed it in 1824 he called it *Reflections on the Motive Power of Fire and on Machines Fitted to Develop That Power*. By *motive power*, Carnot meant the amount of useful work, such as pumping water out of a mineshaft or powering a ship, that can be obtained from the heat that's created in the "fire" or furnace of a steam engine.

Carnot's text is nothing like a modern scientific paper. His desire that it should be "understood by persons occupied with other studies"—by which he meant nonscientists—shines through in its jargon-free, lucid exposition. Before explaining the science, Carnot tries to persuade the reader that the science matters. He stresses the benefits of the way steam engines use heat to perform tasks that hitherto had required animal-muscle power, wind, or flowing water, writing, "They seem destined to produce a great revolution in the civilized world." He even makes the case for the technology's utopian potential: "Steam navigation brings nearer together the most distant nations. It tends to unite the nations of the earth as inhabitants of one country." And as proof of what steam power is capable of, Carnot points across the English Channel: "To take away today from England her steam engines . . . would be to ruin all on which her prosperity depends . . . to annihilate that colossal power."

Carnot ends his introduction with this statement of intent: "Notwithstanding the work of all kinds done by steam engines . . . their theory is very little understood, and the attempts to improve them are still directed almost by chance."

For Carnot, deducing the theory underpinning steam engines was therefore no academic exercise. Doing so, he felt, would provide a way of improving their fuel efficiency, thus reducing costs for his country's industrialists and helping them catch up with their British counterparts. To Carnot, the crucial question was, How does one obtain as much motive power as possible from a steam engine?

Carnot then takes the idea of an engine's duty one step further. Instead of asking how much coal must be burned to raise a known weight a given distance, Carnot asks how much heat must flow out of a furnace to achieve this. Or put another way, if, say, one hundred calories of heat flow out of a furnace, what's the greatest possible height to which this can raise a weight of one kilogram? (For simplicity's sake, think of one unit of "motive power" as the amount that will lift a one kilogram weight by a height of one meter.)

To answer this question, Carnot considers a typical early nineteenth-

Impressionistic view of key aspects
of a Watt engine

century steam engine that works along the lines devised by James Watt. Two aspects greatly interested the Frenchman.

First, Watt had noticed that hot steam exerts a great deal of pressure, more even than the downward weight of the atmosphere. To exploit this, he contrived his engine design so expanding steam from a boiler pushed a piston. (In the diagram, the steam pushes the piston down.)

Second, Watt understood that for the engine to keep going, the piston must return to its starting position at the top of the cylinder. This requires the steam that has pushed it down to be cooled and condensed into water, so it no longer presses down on the piston. Then a portion of the motive power generated in the downward stroke is used to push the piston back up.

Watt enabled this with a device called a condenser that's kept cool by a spray of water. When the piston is near the bottom of the cylinder, the bypass valve and the valve leading to the condenser open. The steam above the piston flows through these valves and is turned into water in the condenser. It thus no longer pushes down on the piston.

In his treatise, Carnot ignores how the engine's components work and instead focuses on the flow of heat through the whole device. Adhering to caloric theory, he argues that a quantity of indestructible caloric fluid, released from the burning coal in a furnace, is "incorporated" into the steam, thus raising its temperature and pressure so it can push down on the piston. Then, in the condenser, the caloric is removed from the steam, causing it to cool and liquefy. As the steam pressure falls, the piston returns.

Carnot's conclusion is that an unchanging amount of caloric flows from the hot furnace to the cold condenser, and this flow generates the motive power of the engine. He equates this to the flow of water. Just as no water is lost as its downward flow drives a mill, so, too, no heat is lost as its "coolward" flow drives a steam engine.

Carnot was wrong to believe in caloric theory, but it did lead to his first insight. A body of water, no matter how vast, will not produce motive power unless it can flow downhill. So, too, even a prodigious quantity of heat will not create motive power if there's no temperature difference it can "flow down." A steam engine inside a vast hot furnace will not work despite the presence of abundant heat because there is no way to cool and liquefy the steam so the piston can be pushed back to the top of the cylinder. Carnot writes:

"The production of heat alone is not sufficient to give birth to the impelling power: it is necessary that there should also be cold; without it, the heat would be useless."

That sentence marks the first step in the history of thermodynamics.

Next, Carnot tackles a question that vexed engineers in his day: Is steam the best substance to use in machines that extract motive power from heat? After all, heating any gas, not just steam, causes it to expand, increasing the pressure it exerts. That means any gas can push a piston. So, can a machine based, say, on atmospheric air or alcohol vapor produce more motive power from a given amount of heat flow than a steam engine? Can such a machine use the heat flowing from burning one kilo-

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A "super-ideal" engine drives an ideal reverse engine.

hol vapor; but the imagined gas he proposes using is *better* than steam. Thus, the engine using it is better than a steam engine, too. How much better, though? Suppose it lifts the fifty-kilogram weight by twelve meters rather than ten for the same flow of one hundred calories of heat between the same furnace and sink.

As before, Carnot analyzes the arrangement in which this "super-ideal" (nonsteam) engine drives the ideal reverse engine. One hundred calories flow into the super-ideal engine. But because it lifts the weight by twelve meters, this can drive the "reverse" engine *and,* say, a water pump. The reverse engine only needs the weight to fall by ten meters to send the hundred calories back to the furnace and replenish it. But with the super-ideal engine, the weight can still drop by another two meters at the end of each loop—twelve as opposed to ten.

This "leftover dropping distance," so to speak, could also be used to pump water. In fact, every loop will generate a surplus of "dropping power." Such a machine would do useful work without ever consuming any fuel.

However, Carnot declares, such a machine cannot exist. It is a perpetual motion machine, which scientists had long declared an impossibility. For centuries, people had dreamed of building devices that did something useful, but which needed no input of effort from animal muscle, flowing water, or wind. None had ever worked, and in 1775 the Royal Academy of Sciences in Paris stated that they would no longer consider proposals concerning perpetual motion. In his text analyzing water mills, Sadi's own father had used this same assumption of the impossibility of perpetual motion to set an upper limit on the amount of useful work that could be extracted from such devices. Sadi Carnot's genius was to realize that the same logic would work with great effect on steam engines. As he writes:

"Do we not know besides, a posteriori, that all the attempts made to produce perpetual motion by any means whatever have been fruitless?—that we have never succeeded in producing a motion veritably perpetual, that is, a motion that will continue forever without alteration in the bodies set to work to accomplish it?"

The impossibility of perpetual motion means, to Carnot, that it is not possible to build an engine that produces more motive power than an ideal steam engine. Or as he puts it:

"Such a creation is entirely contrary to ideas now accepted, to the laws of mechanics and of sound physics. It is inadmissible. We should then conclude that the *maximum of motive power resulting from the employment of steam is also the maximum of motive power realizable by any means whatever.*"

Carnot italicized the conclusion here himself. Far from saying that steam is the best material to use, he's instead arguing that *all ideal engines perform equally well, irrespective of the gas or any working material they use and how they are constructed.* The ideal steam engine may well look very different to an ideal air-based engine, but when working between the same furnace and sink, they will all lift a weight by the same amount. And that means that the working materials in the engine, such as the steam or the air, don't themselves provide any motive power—*that all comes from the heat flow*.

Carnot had considered steam engines in their idealized form and uncovered a truth about their real-world equivalent that no engineer had. Most still felt that the working material used by an engine did play some role in creating motive power.

For a sense of Carnot's reasoning, think of a water mill. For a given flow of water, the maximum power it can produce is limited by the height by which the water drops. No amount of cunning design can improve on this limit. The only way to up the power of the mill is to increase the height that the water drops. Analogously, for any heat engine, the power it can produce from a given flow of heat is limited by the temperature difference between its furnace and sink. The only way to up this is to increase this temperature difference. Conversely, reducing the temperature difference will reduce the power output.

Carnot also analyzed how to maximize the motive power produced by the flow of heat down any given temperature drop. In a typical engine, heat causes a gas like steam to expand and push a piston. In an ideal engine all the heat should go to expanding the gas and not be lost by, say, leakages. (For more details see Appendix I.)

This logic told Carnot that the real steam engines of his day had to be woefully wasteful. The hottest temperature the steam reached as it expanded and pushed a piston was, Carnot reckoned, a little over 160°C. The coldest it fell to as it condensed was around 40°C. That meant steam engines were extracting motive power from a temperature drop of around 120°C. But the temperature in the engine's furnace in which the coal was burning was over 1,000°C, and that meant a much-larger temperature drop—of 900°C or more—was being wasted.

The water mill is again a helpful analogy. Imagine a waterfall with a ten-meter drop. Now picture a waterwheel positioned only one meter below the top rather than at the bottom. Intuitively, one concludes that much of the power of the flowing water is being wasted. Steam engines waste heat flow in a similar way.

How could this be corrected? One way, Carnot argues, is to use atmospheric air as the substance that pushes the piston. Because air contains oxygen, fuel can burn and generate heat inside the cylinder and not in an external boiler as happens in a steam engine. "Considerable loss could thus be prevented" is how Carnot puts it. Air has another advantage—it has a lower "specific heat" than steam. That means, roughly, that the same amount of heat can raise the temperature of a quantity of air by a greater amount than an equivalent quantity of steam. In turn that implies that the same flow of heat can drive an air-based engine between greater temperature differences than a steam-based one. Thus, even more efficiency is achieved. Carnot writes, "The use of atmospheric air for the development of the motive power of heat . . . would doubtless offer a notable advantage over the vapor of water." This prediction was borne out in the late nineteenth century by the arrival of the internal combustion engine, a device that burns petrol or diesel to raise the air temperatures in its cylinders to well over 1,000°. Rudolf Diesel, who published his theories on how to build such an engine in 1893, was inspired by Carnot's ideas.

Carnot's treatise is a magnificent work of science, the product of a fertile imagination that worked in tandem with a mind that reasoned carefully on the basis of evidence. This legacy surrounds us. Internal combustion engines, jets, the giant turbines that generate electricity, and even the rockets that took humans to the moon, all are based on Carnot's discovery that the flow of heat from hot to cold is required to generate motive power. Less obvious, but just as important, is the legacy of Carnot's work to the quest to better understand our universe.

In the summer of 1824 Carnot published *Reflections on the Motive Power of Fire* at his own expense. He was twenty-eight years old. A wiser option might have been for him to submit his work to the widely read journal of his alma mater, the Polytechnic School. But perhaps the style of the *Reflections*, combining sociology, politics, and abstract reasoning, made it unsuitable? In any event, he self-published at a cost of 459.99 francs, which must have been a financial challenge given that he was living on half pay from the French military. Six hundred copies were printed and went on sale on June 12, 1824, at a price of three francs a copy. There is no account of how many were sold. Later that month, however, a summary of his book's ideas was read at a meeting of the Academy of Sciences in Paris, but there is no record of France's leading scientists having any recollection of that presentation and no evidence that Carnot was there to champion it.

Thereafter in the late 1820s, we catch glimpses of Sadi Carnot in the turmoil of French politics. In 1828, for instance, he resigned from the

French military, and following this there's no sign he had any form of employment, except for a letter indicating that he tried to go into business as an engineer.

In the years after the publication of *Reflections on the Motive Power of Fire*, there's a hint that Carnot might have lost faith in his work. Although few of his personal papers survive, one collection, a loose bundle of twenty-three pages, was found by his younger brother. Entitled "Notes on Mathematics, Physics, and Other Subjects," they reveal that Carnot was having doubts about a key assumption in the *Reflections*, namely that heat was an indestructible fluid known as caloric. In reflecting on when heat does something noticeable, such as pushing on a piston, he writes, "The quantity can no longer remain constant." With hindsight, we can read this concern as evidence of impeccable scientific instincts. But to Carnot, it would have cast doubt on his key insight, namely that without cold, heat is useless. Moreover, if heat isn't caloric fluid producing motive power as it flows from hot to cold, his entire hypothesis looks shaky. As Carnot put it in his notes, "It would be difficult to explain why, in the development of the motive power of heat, a cold body is necessary." This problem of how to reconcile Carnot's insight that heat must flow from hot to cold to produce motive power with this imaginary caloric fluid provides the next turn in our story.

Tragically, though, Carnot would play no further part. In 1832, for reasons that remain obscure, Carnot entered a mental asylum in Ivry, on the outskirts of Paris. While he was there, a cholera epidemic swept through France, and Carnot succumbed. Our last glimpse is of Sadi Carnot ravaged by a high fever and in mental anguish, dying with no knowledge of the immense importance of his work. The ledger at the asylum reads, "Mr. Carnot Lazare Sadi, ex-military engineer, admitted 3 August 1832, for mania. Cured of mania. Dead from cholera, 21 August 1832."

He was thirty-six years old.

The Joules, being brewers, prospered. The city's new workers were thirsty, and demand for beer soared to the extent that soon after Joule was born, his father could afford a large house with six servants in the well-to-do neighborhood of Swinton.

Joule, by his own account, was a sickly child—he had regular treatment till the age of twenty for a spinal weakness, which left him with a slightly hunched back. A shy boy, he was deeply attached to his older brother—their parents decided to educate the pair at home so they wouldn't be separated. The family's wealth meant that when Joule was sixteen, his father enrolled him for private lessons with the famous chemist John Dalton.

Joule started work in the family brewery while in his teens and would play an active role in running the business for nearly two decades. In the early years, he attended the brewery daily from 9:00 a.m. to 6:00 p.m. The machinery he encountered there—pumps and vats in which liquids were stirred and heated to precise temperatures—determined the direction of Joule's scientific research. These devices set him on a scientific collision course with Sadi Carnot.

For Carnot, obsessed as he was with steam engines, the key question was how to produce the greatest amount of motive power from a given amount of heat. Joule's surroundings encouraged him to go further, to ask if there might be a better source of motive power than heat. The family brewery did employ a steam engine, and Joule knew how much his business spent on coal. So, with an eye to the bottom line mixed in with a good measure of scientific curiosity, he wondered if a recent invention, the battery-powered electric motor, could drive the brewery's pumps and stirrers more cheaply than burning coal.

Electric motors had been invented in the early 1830s, and within a few years they had become a craze. "Electrical Euphoria" swept the Western world. Societies such as the London Electrical Society convened, Russia's czar and the US government both funded research to see if these new devices could propel boats and pull trains. In Manchester, a magazine called *The Annals of Electricity* appeared. Its editor was a friend of the Joule family, and this obscure periodical would publish much of Joule's early work.

By 1840, ensconced in a laboratory he'd set up in the family home, Joule was building batteries, electromagnets, and motors, and investigating their behavior. One of his earliest observations was his most significant. He noticed that as an electric current runs through a wire, the wire becomes warmer. Electricity, in other words, can produce heat as well as do work by turning a motor. (From now on I shall use the word *work* to mean what Carnot called motive power [i.e., it's a measure of the effort needed to raise a known weight by a known height].)

Electricity's ability to produce heat fueled Joule's suspicion that something was awry with caloric theory, which stated that heat could neither be created nor destroyed. To Joule's eyes, it seemed as if electricity was indeed creating heat as it ran along a wire.

Joule measured this effect with his hallmark diligence and deduced that whether or not caloric theory was true, there is a mathematical relationship between the heat produced, the magnitude of the current, and the resistance of the wire through which it flows. Joule was convinced this was an important discovery, deserving of a wider audience than the readers of the *Annals*, so he sent a paper describing it to Britain's most prestigious scientific publication, *The Transactions of the Royal Society*. Though the equation Joule derived is now taught as part of high school physics and is the basis of every electric toaster, the editor rejected it, allowing only a brief summary to be printed in a lowlier sister journal. It was the first of a series of setbacks Joule would face trying to inform the wider scientific community of his efforts.

Through 1840 and 1841, Joule was becoming ever more skilled at working with electricity, and he focused on comparing the cost of extracting work from an electric motor with that of obtaining it from a steam engine. In Joule's time, batteries consisted of zinc plates that were suspended in a bath of acid. As the zinc dissolved into the acid, electricity was produced, which could power a motor to raise a weight—i.e., do work. In his experimental setup, Joule calculated that the electricity produced as a pound of zinc dissolved could lift a weight of 331,400 pounds by a height of one foot. From a cost perspective, this compared very unfavorably with coal-fired steam engines. In these, burning a pound of coal, a much cheaper material than zinc, could lift a weight five times greater, 1.5 million pounds, to a height of one foot.

This finding killed any idea of replacing the steam engine in his family brewery with an electric motor—"I almost despair of the success of electro-magnetic attractions as an economic source of power," he wrote. But, importantly, it did teach Joule that different ways of producing work are numerically comparable.

Next, Joule started experimenting with dynamos—machines that turn work into electricity. Dynamos, such as the ones attached to bicycle wheels, consist of a wire coil surrounding a magnet. As you pedal, the wheel makes the magnet spin, and this induces an electric current in the coil, which then powers the lights. Joule observed that the electricity produced by a dynamo warms a wire just as that from a battery does. Already suspicious of caloric theory, he now felt he had a way to test it.

To Joule, the ability of an electric current to produce heat had two explanations:

1. Heat was, as most scientists believed, caloric. In which case, to heat up the wires connected to it, the dynamo must be pumping caloric from somewhere within itself to the wires that were warming up. But if that was the case, one would expect the coil within the dynamo to cool down as caloric flowed out of it to the rest of the circuit.

2. Electric current was being *converted* into heat as it flowed through the wires.

So, in late 1842 and early 1843, Joule carried out a series of groundbreaking experiments to determine which explanation was true. He designed a hand-cranked dynamo with a clever modification. He placed the coil in which the electric current is induced inside a glass tube. Joule then filled this with water so he could detect any temperature changes that occurred in the coil. If caloric was real, as Joule turned his dynamo and created electricity, caloric should flow out of the coil, thus cooling the water that enclosed it.

The opposite happened. Far from cooling down, the coil warmed up. Moreover, the more vigorously Joule cranked his dynamo, and the more electric current he produced, the hotter the water in which the coil was submerged became. It seemed that the electricity flowing from and through his dynamo was creating heat and not that the dynamo was moving caloric from one place to another.

To study this further, Joule connected a battery to his dynamo. Before the latter was turned on, electricity flowed from the battery through the dynamo's wire coil and warmed it. That was to be expected—Joule had long ago noted that current from a battery heats a wire. More significant was what happened when Joule cranked the dynamo while it was still connected to the battery. If he rotated the dynamo in one direction, say clockwise, he found the current it generated added to the current flowing from the battery and the water temperature surrounding the coil rose by a greater amount than when the dynamo was not turning. He then cranked the dynamo in the opposite direction, counterclockwise, so the current it generated opposed the current coming from the battery. Now he found that though the water temperature still rose, it did so by a smaller amount. It was as if the electric current from the dynamo was erasing some of the heat that the current from the battery produced.

To Joule, the implications were clear. He wrote with unequivocal confidence, "We have therefore in magneto-electricity an agent capable by simple mechanical means of destroying or generating heat."

The experimental rig Joule had created seemed to him to work in a two-step process. First the work done turning the dynamo generated electricity, and then, as that electricity flowed, it created heat. This implied that the ultimate source of the heat in this arrangement was the work, with the electricity acting as an intermediary.

Joule's next step was to try to quantify this process. If work can be turned into heat, how much of it is needed to create a given quantity of heat? To Joule, work and heat had become interconvertible, the one into the other much like the dollar and the pound. They are both forms of money, and if one knows the exchange rate, one knows how many dollars are equivalent to one pound. Joule believed there was an "exchange rate" between work and heat. Naming this "the Mechanical Equivalent of Heat," he set out to discover its value.

To do so, Joule connected his dynamo to a falling weight via a system of ropes and pulleys. As the weight fell, it turned the dynamo, generating first electricity and then heat, which as before warmed a tube of water. Joule could now equate the height by which a known weight fell to the amount of heat that was created. In other words, he could measure the Mechanical Equivalent of Heat.

Joule defined what he called a "unit of heat" as the amount of heat needed to raise the temperature of a pound of water by 1°F. Joule further declared a unit of work to be the amount provided as a one-pound weight falls by one foot, which he referred to as a foot-pound. Over several weeks Joule ran versions of this experiment over and over with painstaking meticulousness. The process was fiddly and difficult, not least because the heat from the electric current raised the water temperature in the tube by, at most, 3°F, a figure barely discernible on his thermometer. In addition, Joule struggled to insulate his apparatus from the ambient temperature of his room, so that he could ensure any temperature changes were solely due to the electric current generated in his dynamo.

After several weeks of experimental labor, Joule satisfied himself that his results were reliable. Better yet, those results showed there did indeed seem to be a fixed conversion rate between work and heat. The value was hard to pin down exactly—it seemed to lie somewhere between 750 and 1,000 foot-pounds per unit of heat—and so Joule took an average of all his readings.

"The quantity of heat capable of increasing the temperature of a pound of water by one degree of Fahrenheit's scale is equal to, and may be converted into, a mechanical force capable of raising 838 lb. to the perpendicular height of one foot."

To modern eyes Joule may seem to have been a little too eager to believe his results. His confidence stemmed in part from his upbringing and beliefs. Politically conservative and a devout Christian, Joule saw his scientific endeavors as "essentially a holy undertaking," convinced as he was that a divine being had endowed the universe with a fixed amount of an immaterial substance that enabled change and movement. Electricity, work, and heat were simply different facets of this. They might be converted from one to the other, but the total amount was invariable. As Joule wrote toward the end of one of his papers, "The grand agents of nature are, by the Creator's fiat, indestructible; and that wherever mechanical force is expended, an exact equivalent of heat is always obtained."

What Joule called *the grand agents of nature* we today know as *energy*. For what lay behind Joule's religious words was the elaboration of a principle known to scientists today as the conservation of energy and also as the first law of thermodynamics.

In the summer of 1843, hoping to promote his discovery, Joule traveled to Cork, on the south coast of Ireland, to attend a meeting of the British Association for the Advancement of Science. The BAAS had been founded a decade earlier by British scientists frustrated by the elitist and conservative character of the Royal Society. The word *scientist* was mooted at their first meetings. The purpose of the term was to unite under a single banner "students of the knowledge of the material world." The BAAS rated Joule's work highly enough to invite him to speak about the Mechanical Equivalent of Heat, but, as he later reported, "the subject did not excite much general attention." Why? One factor was that Joule was an outsider finddipitous. Finally, after a decade of scientific obscurity, chance had placed someone in the audience who seemed interested in Joule's work. At the end of the talk, a young man stood up and began asking questions, creating "a lively interest in the new theory." The interrogator was a twenty-three-year-old from Glasgow named William Thomson, who was already regarded as one of his nation's leading scientific minds. Years later he, too, vividly recalled the encounter and the feelings of both intrigue and alarm it had evoked: "I felt strongly impelled at first to rise and say that Joule must be wrong," but "as I listened on and on, I saw that Joule had certainly a great truth and a great discovery, and a most important measurement to bring forward."

At the time, Joule's "great discovery" presented Thomson with an uncomfortable dilemma. Over the previous two years, he'd fallen in love with Sadi Carnot's elegant analysis of the way an unchanging amount of caloric produces work as it flows from a hot furnace to a cold sink. Yet, here was this unassuming Mancunian claiming caloric did not exist. The easy option, taken by many others in the room, would have been to dismiss Joule's evidence—much of it was based, after all, on minuscule temperature increases discernible only on novel thermometers.

William Thomson, however, possessed remarkable scientific intuition. In his mind, Carnot's theory and Joule's experiments both rang true despite appearing incompatible. Could they both be right? If so, how?

Decades later, William Thomson, ennobled as Lord Kelvin for his contributions to science, embellished the story of the Oxford encounter while unveiling a statue of Joule. According to Thomson, while on a walking holiday a few weeks after that first meeting, he'd run into Joule near the Alpine resort town of Chamonix. Joule was on his honeymoon, but he'd left his bride in a nearby carriage while, thermometer in hand, he searched for a waterfall to confirm a theory that the temperature at the top is cooler than at the bottom. A fortnight later, Joule was still on this quest, and Thomson even joined him in attempting to measure temperature differences at the Cascades de Sallanches. Thomson may, however, have invented this anecdote to convey Joule's unwavering commitment to science. In a letter to his father written shortly after the Alpine meeting, he makes no reference to thermometers or waterfall temperatures. But when Thomson recounted the tale in later life, he described it as "one of the most valuable recollections of my life."

CHAPTER FOUR

The Valley of the Clyde

Caino? Je ne connais pas cet auteur.
—Paris bookseller to William Thomson

In 1845, two years before the encounter in Oxford, while Joule was laboring in his home laboratory in Manchester, William Thomson was traipsing the streets of Paris from bookshop to bookshop searching for Sadi Carnot's treatise, *Reflections on the Motive Power of Fire*. Thomson had come across a description of *Reflections* in a French scientific journal, and what he'd read had fired his imagination. It represented a breakthrough, he became convinced, in the understanding of heat. But because of the inquirer's Scottish-accented French, the booksellers struggled to recognize the name of the author whose book he was seeking. Even when he managed to clarify it by overemphasizing the *r* in Carnot, he was offered a book on "some social question" by Sadi's brother, the politician Hippolyte Carnot.

Thomson was in Paris undergoing the final stages of an education designed from boyhood to prepare him for scientific greatness. Born in Belfast in 1824, he'd moved to Glasgow eight years later with his family when his father had been appointed mathematics professor at the city's university. Aged fifteen, Thomson won the class prize at the same institution for an analysis of how the earth's shape had formed. A year later his precocious mathematical talent further manifested when he encountered *The Analytical Theory of Heat* by the French polymath Joseph Fourier. This text was striking in that it made no claim as to what heat is. Fourier's aim was to mathematically describe how heat behaves and, in particular, how it flows. An example is a metal bar that is hot at one end and cold at the other. Experience tells us that heat will diffuse from hot to cold until the bar's temperature equalizes. Fourier showed how this kind of diffusion can be described mathematically. His approach was unusual for the time, and Fourier had critics. Aged sixteen, Thomson published a detailed defense of the Frenchman's methods in the scholarly *Cambridge Mathematics Journal*.

Proudly aware of Thomson's talent, his father urged him to study mathematics at Cambridge. Over the previous two decades, a new generation of professors there had embraced the latest developments in the subject from Europe, and the university had regained its reputation as the nation's preeminent center for mathematical training. At Cambridge, Thomson's peers and teachers confirmed his promise. Senior academics who read his essays were surprised to learn the author was still a teenager.

Meanwhile, Thomson's father began hatching a plan for him to become Glasgow University's next professor of natural philosophy. (Later in the nineteenth century, this phrase was replaced with the modern term *physicist*.) With the incumbent old and in poor health, Thomson senior's one concern was that the post would not be open to a youthful candidate whose only credentials were a Cambridge mathematics degree—a qualification that showed a talent for abstract reasoning but not necessarily for demonstrating physical phenomena to students, a highly valued skill at Glasgow University, the leading educational establishment in an industrial city that prized practicality. Thomson senior had heard, however, that France led the way when it came to teaching science by demonstration. He urged his son to obtain letters of introduction to eminent French savants, travel to Paris, and get his hands dirty once he'd received his Cambridge degree.

In Paris, Thomson worked as an assistant to an experimental physicist, Victor Regnault, who had been funded by the French government to study the thermal properties of steam. (Regnault, like Carnot, had benefited from the French revolutionary government's commitment to widespread education. Orphaned at eight and impoverished, he had won a place at the Polytechnic School and had gone on to become one of France's leading scientists.) Working in Regnault's laboratory, even in a lowly capacity, holding test tubes or operating an air pump, was a transformative experience for the young Thomson. He observed firsthand how water and steam behave when heated and cooled. Shadowing the diligent Regnault also taught

Thomson the importance of patience and precision in experimental physics. And crucially, it was in Paris—"without doubt the Alma Mater of my scientific youth"—where Thomson encountered the ideas of Sadi Carnot.

In April 1845, Thomson returned to Britain, where, as his ailing predecessor clung to life, he had to wait another year for the Glasgow professorship to become available. In the interim, Thomson made ends meet by coaching Cambridge undergraduates and continued to mull what he had gleaned of Carnot's ideas. He discussed them in detail with his older brother by two years, James, who was a gifted scientist in his own right. Though always coming second to William, he'd excelled as a student at Glasgow University, and then worked as an apprentice to several firms in England and Scotland. James had a passion for engineering—"He talks about it ceaselessly all day"—and he and William were a formidable scientific double act. William had mathematical skills and a good grasp of laboratory physics. James had hands-on experience working with real steam engines. William's mind was sharp and mobile, James's dogged and stubborn. The pair loved nothing better than to discuss science and engineering, although listening in wasn't easy: "It is really quite comic to see how both brothers talk at one another, and neither listens."

To the Thomson brothers, Carnot's analysis rang true. Its abstract reasoning appealed to William, and James saw it in action, particularly because of the time he'd spent working on steam engines intended for ships. These forced their builders to focus on efficiency, even if coal was cheap. The weight of the fuel limited how much a ship could carry and how far it could go. Intuitively, James felt it was wasteful that these engines' condensers operated at warmer temperatures than that of the surrounding sea or ocean. (The condenser is where steam is turned back into water, so it no longer presses on the piston.) To James, this meant that the heat in the condenser was being wasted as it wasn't doing any work. If a way could be found to condense steam at the same temperature as the ocean, then, James believed, ships could go farther without consuming more coal. This view chimed with Carnot's analysis—"a very beautiful piece of reasoning" is how James described it to William.

In September 1846, the professor of natural philosophy at Glasgow died, and William Thomson, then only twenty-two, took up his post. Here he set up Britain's first physics laboratory in which undergraduate students took part in laboratory work. Thomson was an enthusiastic teacher on the piston. You would feel a resisting pressure from the piston on your hands. In the same way in James Thomson's hypothetical ice engine, as the water freezes, the pressure on it from the piston would increase.

In Thomson's time, water was known to freeze at 0°C on the earth's surface, where the only pressure acting on it is the weight of our planet's atmosphere. (Scientists refer to this as a pressure of "one atmosphere.") But it was not known whether water's freezing point would change if subjected to higher pressures. If these caused ice to form below 0°C, then Carnot's theory would be saved. Because in that case, as the water turns to ice and produces work, the temperature drops from 0°C to whatever the freezing point of water is when it's under pressure from the piston.

James Thomson calculated the amount by which the freezing point of water must drop as the pressure on it increases for the theory to hold. He worked out that for every increase of pressure by one atmosphere, the freezing point of water should drop by 0.0075°C. So, at a pressure of two atmospheres, water should freeze at minus 0.0075°; and at a pressure of three atmospheres, it should freeze at minus 0.0150°, and so on.

On reading these calculations, William Thomson was elated. He now had a way of testing Carnot's theory in his laboratory at Glasgow University. If he could measure the drop in the freezing point of water as it's put under pressure to be a value predicted by his brother, it would provide evidence that Carnot's theory was correct.

Of course, such an experiment presented huge practical difficulties, not least because the predicted fall in temperature predicted was tiny—too tiny for thermometers of the time to detect. So, in late 1849, William Thomson commissioned one of his students, Robert Mansell, to build a thermometer sensitive enough to detect temperature changes of less than one one-hundredth of a degree Celsius. Mansell had had training in practical engineering prior to enrolling at Glasgow University, and he also had knowledge of glassworking. He took painstaking efforts to calibrate the thermometer to the point where Thomson felt its readings were reliable. Then Thomson filled a glass cylinder with water, which he could press down on with a piston. With this arrangement, Thomson measured the temperature at which water froze under differing amounts of pressure.

Much to William Thomson's satisfaction, the results vindicated his brother and, by extension, Carnot. James Thomson's theory predicted that