“Riveting.”
LOS ANGELES TIMES

THE MOST POWERFUL IDEA IN THE WORLD

A Story of Steam, Industry & Invention

WILLIAM ROSEN

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The MOST POWERFUL IDEA *in the* WORLD

WILLIAM ROSEN

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PROLOGUE

ROCKET

concerning ten thousand years, a hundred lineages, and two revolutions

ON THE GROUND FLOOR of the Science Museum in London's South Kensington neighborhood, on a low platform in the center of the gallery called "Making of the Modern World," is the most famous locomotive ever built.

Or what remains of it. *Rocket,* the black and sooty machine on display, designed and built in 1829 by the father and son engineers George and Robert Stephenson, no longer much resembles the machine that inaugurated the age of steam locomotion. Its return pipes are missing. The pistons attached to the two driving wheels are no longer at the original angle. The yellow paint that made it shine like the sun nearly two centuries ago is now not even a memory. Even so, the technology represented in the six-foot-long boiler, the linkages, the flanged wheels, and even in the track on which it rode are essentially the same as those it used in 1829. In fact, they are the same as those used for more than a century of railroading.

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The importance of *Rocket* doesn't stop there. While the machine does, indeed, mark the inauguration of something pretty significant—two centuries of mass transportation—it also marks a culmination. Standing in front of *Rocket,* a museum visitor can, with a little imagination, see the thousand threads that lead from the locomotive back to the very beginning of the modern world. One such thread can be walked back to the first metalworkers who figured out how to cast the iron cylinders that drove *Rocket*'s wheels. Another leads to the discovery of the fuel that boiled the water inside that iron boiler. A third—the shortest, but probably the thickest—leads back to the discovery that boiling water could somehow be transformed into motion. One thread is, actually, thread: *Rocket* was built to transport cotton goods—the signature manufactured item of the first era of industrialization—from Manchester to Liverpool.

Most of the threads leading from *Rocket* are fairly straightforward, but one—the most interesting one—forms a knot: a puzzle. The puzzle of *Rocket* is why it was built to travel from Manchester to Liverpool, and not from Paris to Toulouse, or Mumbai to Benares, or Beijing to Hangzhou. Or, for that matter, since the world's first working model of a steam turbine was built in first-century Alexandria, why *Rocket* started making scheduled round trips at the beginning of the nineteenth century instead of the second.

Put more directly, why did this historical discontinuity called the Industrial Revolution—sometimes the "First" Industrial Revolution—occur when and where it did?*

The importance of that particular thread seems self-evident. At just around the time *Rocket* was being built, the world was ex-

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* The term didn't really start to get traction until 1884, when a collection of lectures given by the economic historian Arnold Toynbee (the uncle of the famous one) at Balliol College starting in 1878 was posthumously published under the title *Lectures on the Industrial Revolution of the 18th Century in England, Popular Addresses, Notes, and Other Fragments*. This post hoc designation does have some arbitrariness to it; the most frequent textbook dates for the Industrial Revolution, 1760–1820, are a consequence of the fact that Toynbee's ostensible lecture subject was George III, whose regnal dates they are.

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periencing not only a dramatic change *in* industry—what *The Oxford English Dictionary* calls “the rapid development in industry owing to the employment of machinery”—but also a transition *to* industry (or an industrial economy) from agriculture. Combining the two was not only revolutionary; it was unique.

“Revolutionary” and “unique” are both words shiny with overuse. Every century in human history is, in some sense, unique, and every year, somewhere in the world, something revolutionary seems to happen. But while love affairs, epidemics, art movements, and wars are all different, their effects almost always follow one familiar pattern or another. And no matter how transformative such events have been in the lives of individuals, families, or even nations, only twice in the last ten thousand years has something happened that truly transformed all of humanity.

The first occurred about 10,000 BCE and marks the discovery, by a global human population then numbering fewer than five million, that they could cultivate their own food. This was unarguably a world changer. Once humanity was tethered to the ground where its food grew, settled societies developed; and in them, hierarchies. The weakest members of those hierarchies depended on the goodwill of the strongest, who learned to operate the world’s longest-lasting protection racket. Settlements became towns, towns became kingdoms, kingdoms became empires.

However, by any quantifiable measure, including life span, calories consumed, or child mortality, the lived experience of virtually all of humanity didn’t change much for millennia after the Agricultural (sometimes known as the Neolithic) Revolution spread around the globe. Aztec peasants, Babylonian shepherds, Athenian stonemasons, and Carolingian merchants spoke different languages, wore different clothing, and prayed to different deities, but they all ate the same amount of food, lived the same number of years, traveled no farther—or faster—from their homes, and buried just as many of their children. Because while they made a lot more children—worldwide population grew a hundredfold between 5000 BCE and 1600 CE, from 5 to 500 million—they didn’t make much of anything else. The best estimates

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for human productivity (a necessarily vague number) calculate annual per capita GDP, expressed in constant 1990 U.S. dollars, fluctuating between $400 and $550 *for seven thousand years.* The worldwide per capita GDP in 800 BCE—$543—is virtually identical to the number in 1600. The average person of William Shakespeare's time lived no better than his counterpart in Homer's.

The first person to explain why the average human living in the seventeenth century was as impoverished as his or her counterpart in the seventh was the English demographer Thomas Malthus, whose *Essay on the Principle of Population* demonstrated that throughout human history, population had always increased faster than the food supply. Seeking the credibility of a mathematical formula (this is a constant trope in the history of social science), he argued that population, unless unchecked by war, famine, epidemic disease, or similarly unappreciated bits of news, always increased geometrically, while the resources needed by that population, primarily food, always increased arithmetically.* The "Malthusian trap"—the term has been in general use for centuries—ensured that though mankind regularly discovered or invented more productive ways of feeding, clothing, transporting or (more frequently) conquering itself, the resulting population increase quickly consumed all of the surplus, leaving everyone in precisely the same place as before. Or frequently way behind, as populations exploded and then crashed when the food ran out. Lewis Carroll's Red Queen might have written humanity's entire history on the back of a matchbook: "Here, you see, it takes all the running you can do, to keep in the same place. If you want to get somewhere else, you must run at least twice as fast as that."

This is why *Rocket*'s moment in history is unique. That soot-blackened locomotive sits squarely at the deflection point where a line describing human productivity (and therefore human wel-

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* "Geometric" and "arithmetic" are Malthus's terms; the modern equivalents are "exponential" and "linear."

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fare) that had been flat as Kansas for a hundred centuries made a turn like the business end of a hockey stick. *Rocket* is when humanity finally learned how to run twice as fast.

It's still running today. If you examined the years since 1800 in twenty-year increments, and charted every way that human welfare can be expressed in numbers—not just annual per capita GDP, which climbed to more than $6,000 by 2000, but mortality at birth (in fact, mortality at any age); calories consumed; prevalence of infectious disease; average height of adults; percentage of lifetime spent disabled; percentage of population living in poverty; number of rooms per person; percentage of population enrolled in primary, secondary, and postsecondary education; illiteracy; and annual hours of leisure time—the chart will show every measure better at the end of the period than it was at the beginning. And the phenomenon isn't restricted to Europe and North America; the same improvements have occurred in every region of the world. A baby born in France in 1800 could expect to live thirty years—twenty-five years less than a baby born in the Republic of the Congo in 2000. The nineteenth-century French infant would be at significantly greater risk of starvation, infectious disease, and violence, and even if he or she were to survive into adulthood, would be far less likely to learn how to read.

Think of it another way. A skilled laborer—a weaver, perhaps, or a blacksmith—in seventeenth-century England, France, or China spent roughly the same number of hours a week at his trade, producing about the same number of bolts of cloth, or nails, as his ten-times great-grandfather did during the time of Augustus. He earned the same number of coins a day and bought the same amount, and variety, of food. His wife, like her ten-times great-grandmother, prepared the food; she might have bought her bread from a village baker, but she made pretty much everything herself. She even made her family's clothing, which, allowing for the vagaries of weather and fashion, was largely indistinguishable from those of any family for the preceding ten centuries: homespun wool, with some linen if flax were locally available. The laborer and his wife would have perhaps eight or

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ten live offspring, with a reasonable chance that three might survive to adulthood. If the laborer chose to travel, he would do it on foot or, if he were exceptionally prosperous, by horse-drawn cart or coach, traveling three miles an hour if the former, or seven if the latter—again, the same as his ancestor—which meant that his world was not much larger than the five or six miles surrounding the place he was born.

And then, for the first time in history, things changed. And they changed at the most basic of levels. A skilled fourth-century weaver in the city of Constantinople might earn enough by working three hours to purchase a pound of bread; by 1800, it would cost a weaver working in Nottingham at least two. But by 1900, it took less than fifteen minutes to earn enough to buy the loaf; and by 2000, five minutes. It is a cliché, but nonetheless true, to recognize that a middle-class family living in a developed twenty-first-century country enjoys a life filled with luxuries that a king could barely afford two centuries ago.

This doesn't mean the transformation happened suddenly. A small but vocal minority of scholars doubts the reality of anything revolutionary, or even industrial, about the phenomenon. Recent studies have demonstrated far less growth in productivity and incomes during the period 1760–1820 than once thought, partly because the income of preindustrial Europe was a lot higher than previously believed. And indeed, Europe, from at least the ninth century onward, had urban centers, roads, and huge amounts of trade traveling along the latter to the former.

On the other hand, the fact that the transformation happened over the course of a century doesn't make it any less revolutionary. Clearly, *something* happened.

Not everyone believes that the something is the contraption sitting in that gallery in the Science Museum. There are, by popular consensus, more than two hundred different theories in general circulation purporting to explain the Industrial Revolution. They include the notion, first popularized by the pioneer sociologist Max Weber, that the Protestantism of Northern Europe was more congenial to innovation than Chinese Confucianism, or the

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Catholicism of France and Southern Europe. Or that China's lack of access to raw materials, particularly coal, sabotaged an Asian Industrial Revolution. For those of a certain mindset, there is a theory that England's absence of internal tariffs and deficiency in landholding peasantry made the leap to industrialization a short one. Was industrialization the result of revenue from overseas colonies? Relatively high labor costs among the lower classes? Relatively large families among the upper classes? Class conflict? The *lack* of class conflict?

All of these explanations, even when reduced to bumper sticker size, are in some sense true. There are dozens of ways to untie a knot, and many will be referred to in later chapters of this book. Their only real liability, in fact, is that they tend to understate the most obvious explanation, which is that the Industrial Revolution was, first and foremost, a revolution in *invention.* And not simply a huge increase in the number of new inventions, large and small, but a radical transformation in the process of invention itself.

Given the importance of mechanical invention to every generation of humanity since some anonymous Sumerians stuck a pole through the center of a hollow tree trunk and rolled the first wheel past their neighbors, it's somewhat puzzling that it took so long to come up with a useful theory of just what invention *is.* Contemporary cognitive scientists have proposed a dozen different strategies and typologies of invention, but one of the most influential remains the eighty-year-old theory of an economic historian with the Dickensian name of Abbott Payson Usher.

Though dense, out of date, and little consulted today, *The History of Mechanical Inventions,* published by the then forty-six-year-old Usher in 1929, documents, at sometimes exhausting length, the ways in which humanity has engaged in a continuous process of improving life by inventing machines, from the earliest plows used by Middle Eastern farmers to the ships, engines, and railroads of the mid-nineteenth century (though, interestingly enough, not the age of electricity during which Usher wrote). Like *Origin of Species,* whose theory was buttressed by thousands of

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examples from the world of nature, *The History of Mechanical Inventions* contains an imposing list of examples, from the harnesses worn by prehistoric draft animals, Egyptian waterwheels and hand querns, to antique beam presses, medieval grain mills, water clocks, and, of course, the steam engine. But it does more than just chronicle human ingenuity. It also presents what is still the most analytically persuasive historical *theory* of invention: Usher, more than anyone else, gives us a toolkit that can be used to analyze and describe just how *Rocket* (and its component parts) was imagined, designed, and constructed.

Before Usher, historians of science hadn't wandered very far from the same two paths that general historians had trod before them. The first is popularly known as the "Great Man" theory of history, in which events are understood through the actions of a few major actors—in this context, the "Great Inventor" theory—while the second perceives those same events as consequences of immutable laws of history; for the history of science and technology, this frequently meant explaining things as a sort of evolution of inventions by natural selection. Usher hated them both. He was, philosophically and temperamentally, a small-*d* democrat who was utterly convinced that the ability to invent was widely distributed among ordinary people, and that the impulse to invent was everywhere.

If the phenomenon of invention were as natural as breathing, one might expect that it would—like breathing—behave pretty much the same whether it occurred in second-century Egypt or eighteenth-century England, and so indeed it did for Usher. To him, every invention inevitably followed a four-step sequence:

1. Awareness of an unfulfilled need;
2. Recognition of something contradictory or absent in existing attempts to meet the need, which Usher called an "incomplete pattern";
3. An all-at-once insight about that pattern; and
4. A process of "critical revision" during which the insight is tested, refined, and perfected.

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Usher is an invaluable guide to the world of inventing, and in the pages that follow, his step-by-step description of the inventive process will be referred to many times. But precisely because his sequence applies to everything from Neolithic digging sticks to automated looms, it cannot explain *why*—in the unforgettable line of the imagined schoolboy introducing T. S. Ashton's short but indispensable history of the Industrial Revolution—"About 1760, a wave of gadgets swept over England." If the process of thinking up "gadgets" was, at bottom, the same for Archimedes, Leonardo, and James Watt, why did it take until the middle of the eighteenth century for a trickle to become a wave?

Even defining the Industrial Revolution as a wave of gadgets doesn't, by itself, place steam power—*Rocket*'s motive force—at the crest of that wave. After all, the early decades of European industrialization were largely driven by water and wind rather than steam. As late as 1800, Britain's water mills were producing more than three times as much power as its steam engines, and this book could, conceivably, have begun not with *Rocket,* but with another display in the "Making of the Modern World" gallery: Richard Arkwright's cotton spinning machine, known as the "water frame" because of its power source.* Nonetheless, the steam engine *was* the signature gadget of the Industrial Revolution, though not because it represented a form of power not dependent on muscle; both waterwheels and windmills had already done that. Nor was it the steam engine's enormous capacity for rapid improvement—far greater than either water or wind power.

The real reason steam power dominates every history of the Industrial Revolution is its central position connecting the era's technological and economic innovations: the hub through which the spokes of coal, iron, and cotton were linked. The steam engine was first invented to drain the mines that produced the coal burned in the engine itself. Iron foundries were built to supply the boilers for the steam engines that operated forges and blast furnaces. Cotton traveled to the British Isles on steamships, was

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* For more about Arkwright—*much* more, in fact—see chapter 10.

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spun into cloth by steam-powered mills, and was brought to market by steam locomotives. Thousands of innovations were necessary to create steam power, and thousands more were utterly dependent upon it, from textile factories—soon enough, even the water frame was steam-driven—to oceangoing ships to railroads. After thousands of years of searching for a perpetual motion machine, the inventors of the steam engine at *Rocket*'s heart created something even better: a perpetual *innovation* machine, in which each new invention sparked the creation of a newer one, ad—so far, anyway—infinitum.

Perpetual technological innovation is so much a part of contemporary life that it is difficult even to imagine the world without it. It is the modern world, however, that is historically anomalous. Hundreds of different cultures had experienced bursts of inventiveness and economic growth before the eighteenth century—bursts they were unable to sustain for more than a century or so. Imagine, for example, how different the last eight hundred years might have been had the Islamic Golden Age—whose inventors were responsible for everything from crankshaft-driven windmills and water turbines to the world's most advanced mechanical clocks—survived the thirteenth century. Instead, like all the world's earlier explosions of invention, it, in the words of one of the phenomenon's most acute observers, "fizzled out." One unique characteristic of the eighteenth-century miracle was that it was the first that didn't.

The other one, and the real reason that the threads leading from *Rocket* form such a challenging knot, is that the miracle was, overwhelmingly, produced by English-speaking people. *Rocket* incorporates hundreds of inventions, small and large—safety valves, feedback controls, return flues, condensers—to say nothing of the iron foundries and coal mines that supplied its raw materials. If one could magically edit out those steam engines invented in Italy, or Sweden, or—more important—France, or China, *Rocket* would still run. If the same magic were applied to those invented in England, Scotland, Wales, and America, the platform in the Science Museum would be empty.

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That is a puzzle for which there is no shortage of proposed solutions (see Industrial Revolution, Theories of, above). The one proposed by the book you hold in your hands can be boiled down to this: *The best explanation for the preeminence of English speakers in lifting humanity out of its ten-thousand-year-long Malthusian trap is that the Anglophone world democratized the nature of invention.*

Even simpler: Before the eighteenth century, inventions were either created by those wealthy enough to do so as a leisure activity (or to patronize artisans to do so on their behalf), or they were kept secret for as long as possible. In England, a unique combination of law and circumstance gave artisans the incentive to invent, and in return obliged them to share the knowledge of their inventions. Virginia Woolf's famous observation—that "on or about December, 1910, human character changed"—was not only cryptic, but about a century off. Or maybe two. Human character (or at least behavior) was changed, and changed forever, by seventeenth-century Britain's insistence that ideas were a kind of property. This notion is as consequential as any idea in history. For while the laws of nature place severe limits on the total amount of gold, or land, or any other traditional form of property, there are (as it turned out) no constraints at all on the number of potentially valuable ideas. The result was that an entire nation's unpropertied populace was given an incentive to produce them, and to acquire the right to exploit them.

OBSERVE ANY GROUP OF people, and you can, if you're so inclined, find clues to their ancestry in their hair or skin color. Examine blood or skin cells under a microscope, and you can learn still more; sequence your subjects' DNA, and you'll know quite a bit indeed, including the portion of the planet where their many-times great-grandparents lived, and genetic relationships between and among them.

Stand in front of *Rocket,* and you'll likely see "only" a rather complicated machine. But examine it with a historian's micro-

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scope, and it will become clear that the “genetic sequence”* of the locomotive, and of the Industrial Revolution it exemplifies, comprises a hundred lineages taken from a dozen different disciplines, as ornate and as complicated as the family tree of a European royal family. The birth of steam depended on a new understanding of the nature of air, and its absence; on an empirical, not yet scientific, understanding of thermodynamics; and on a new language of mechanics describing how matter moves other matter. It was utterly dependent on a new “iron age” inaugurated by several generations of a single English family; a change in the understanding of national wealth, itself a contribution from the Scottish Enlightenment, and of the special character of water as a medium for storing and releasing heat. Perhaps the most important father of the steam engine was the notion that ideas were property, itself the progeny of one of England’s greatest jurists, and her most famous political philosopher. The threads tied to *Rocket* lead back to an Oxford college and a Birmingham factory, to Shropshire forges and Cornish mines, to a Yorkshire monastery and a Virginia flour mill, to a Westminster courtroom and a Piccadilly locksmith. Those threads end at some of history’s great eureka moments: an Edinburgh professor’s discovery of carbon dioxide; an expatriate American’s demonstration that heat and motion are two ways of thinking about the same thing; even a Greek fisherman’s discovery of a first-century calculating machine. All of them—metallurgy and legal advocacy, chemistry and kinematics, physics and economics—are on display in the pages that follow.

But most of these pages are about invention itself. No one can stand in front of *Rocket* for long without pondering the history of this peculiarly human activity, its psychology, economics, and social context. The narrative of steam may be constrained by the limits of mechanics, but it is defined by the behavior of inventors, and the pages that follow attempt to explore not only what inventors actually *do,* but what happens inside their skulls while they

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* The term is a favorite of A. P. Usher.

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do it, touching on recent discoveries in neurobiology, cognitive science, and evolutionary sociology.

Ever since humanity became bipedal, it has invented things. Stone tools in east Africa 2.4 million years ago, pottery in Anatolia eight thousand years ago. Five thousand years later, Archytas of Tarentum described the pulley, and Archimedes—probably—invented the lever, screw, and wedge. For a thousand centuries, the equation that represented humanity's rate of invention could be plotted on an X-Y graph as a pretty straight line; sometimes a little steeper, sometimes flat. Then, during a few decades of the eighteenth and nineteenth centuries, in an island nation with no special geographic resource, a single variable changed in that equation. The result was a machine that changed everything, up to and including the idea of invention itself. The components of *Rocket,* and therefore the Industrial Revolution, are not gears, levers, and boilers, but *ideas* about gears, levers, and boilers—the most important ideas since the discovery of agriculture.

But here is the difference: Many societies discovered agriculture independently, from the Fertile Crescent to the Yangtze to the Indus River Valley. The miracle of sustainable innovation has a single source, a single time and place where mankind first made the connection between invention, power, and wealth, and discovered the most powerful idea in the world.

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THE MOST POWERFUL IDEA IN THE WORLD

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CHAPTER ONE

CHANGES IN THE ATMOSPHERE

concerning how a toy built in Alexandria failed to inspire, and how a glass tube made in Italy succeeded; the spectacle of two German hemispheres attached to sixteen German horses; and the critical importance of nothing at all

TO GET TO CROFTON from Birmingham, you take the M5 south about sixty miles to Brockworth and then change to the A417, which meanders first east, then southwest, then southeast, for another forty-six miles, changing, for no apparent reason, into the A419, and then the A436. In Burbage, you turn left at the Wolfhall Road and follow it another mile, across the railroad tracks and over the canal. The reason for making this three-hour journey (not counting time for wrong turns) is visible for the last quarter-mile or so: two red brick buildings next to a sixty-foot-tall chimney.

The Crofton Pump Station in Wiltshire contains the oldest steam engine in the world still doing the job for which it was designed. Every weekend, its piston-operated beam pumps twelve tons of water a minute into six eight-foot-high locks along the hundred-mile-long Kennet and Avon Canal. The engine itself, number 42B—the figure "B.42" is still visible on the engine

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beam—is so called because it was the second engine with a forty-two-inch cylinder produced by the Birmingham manufacturer Boulton & Watt. It was entered in the company's order book on January 11, 1810, and installed almost precisely two years later. Except for a brief time in the 1960s, it has run continuously ever since.

First encounters with steam power are usually unexpected, inadvertent, and explosive; the cap flying off a defective teakettle, for example. No surprise there; the expansive property of water when heated past a certain point was known for thousands of years before that point was ever measured, and to this day it's what drives the turbine that generates most of our electricity, including that used to power the light by which you are reading this book. The relationship between the steam power of a modern turbine and the kind used to pump the water out of the Kennet and Avon Canal is, however, anything but direct. By comparison, the mechanism of engine 42B is a thing of Rube Goldberg–like complexity, with levers, cylinders, and pistons yoked together by a dozen different linkages, connecting rods, gears, cranks, and cams, all of them moving in a terrifyingly complicated dance that is at once fascinating, and eerily quiet—enough to occupy the mechanically inclined visitor, literally, for hours. When the engine is "in steam," it somehow causes the twenty-six-foot-long cast iron beams to move, in the words of Charles Dickens, "monotonously up and down, like the head of an elephant in melancholy madness."

There is, however, something odd about the beams, or rather about the pistons to which they are attached. The pistons aren't just being driven *up* by the steam below them. The power stroke is also *down:* toward the steam chamber. Something is sucking the pistons downward. Or, more accurately, nothing is: a vacuum.

Using steam to create vacuum was not the sort of insight that came an instant after watching a teakettle lid go flying. It depended, instead, on a journey of discovery and diffusion that took more than sixteen centuries. By all accounts the trip began sometime in the first century CE, on the west side of the Nile Delta, in

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the Egyptian city of Alexandria, at the Mouseion, the great university at which first Euclid and then Archimedes studied, and where, sometime around 60 CE, another great mathematician lived and worked, one whose name is virtually always the first associated with the steam engine: Heron of Alexandria.

The *Encyclopaedia Britannica* entry for Heron—occasionally, Hero—is somewhat scant on birth and death dates; as is often the case with figures from an age less concerned with such trivia, it uses the abbreviation "fl." for the latin *floruit,* or "flourished." And flourish he did. Heron's text on geometry, written sometime in the first century but not rediscovered until the end of the nineteenth, is known as the *Metrika,* and includes both the formula for calculating the area of a triangle and a method for extracting square roots. He was even better known as the inventor of a hydraulic fountain, a puppet theater using automata, a wind-powered organ, and, most relevantly for engine 42B, the *aeolipile,* a reaction engine that consisted of a hollow sphere with two elbow-shaped tubes attached on opposite ends, mounted on an axle connected to a tube suspended over a cauldron of water. As the water boiled, steam rose through the pipe into the sphere and escaped through the tubes, causing the sphere to rotate.

Throughout most of human history, successful inventors, unless wealthy enough to retain their amateur status, have depended on patronage, which they secured either by entertaining their betters or glorifying them (sometimes both). Heron was firmly in the first camp, and by all accounts, the aeolipile was regarded as a wonder by the wealthier classes of Alexandria, which was then one of the richest and most sophisticated cities in the world. Despite the importance it is given in some scientific histories, though, its real impact was nil. No other steam engines were inspired by it, and its significance is therefore a reminder of how quickly inventions can vanish when they are produced for a society's toy department.

In fact, because the aeolipile depended only upon the expansive force of steam, it should probably be remembered as the first in a line of engineering dead ends. But if the inspirational value of

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Heron's steam turbine was less than generally realized, that of his writings was incomparably greater. He wrote at least seven complete books, including *Metrika,* collecting his innovations in geometry, and *Automata,* which described a number of self-regulating machines, including an ingenious mechanical door opener. Most significant of all was *Pneumatika,* less for its descriptions of the inventions of this remarkable man (in addition to the aeolipile, the book included "Temple Doors Opened by Fire on an Altar," "A Fountain Which Trickles by the Action of the Sun's Rays," and "A Trumpet, in the Hands of an Automaton, Sounded by Compressed Air," a catalog that reinforces the picture of Heron as antiquity's best toymaker) than for a single insight: that the phenomenon observed when sucking the air out of a chamber is nothing more than the pressure of the air around that chamber. It was a revelation that turned out to be utterly critical in the creation of the world's first steam engines, and therefore of the Industrial Revolution that those engines powered.

The idea wasn't, of course, completely original to Heron; the idea that air is a source of energy is immeasurably older than science, or even technology. Ctesibos, an inventor and engineer born in Alexandria three centuries before Heron, supposedly used compressed air to operate his "water organ" that used water as a piston to force air through different tubes, making music.

Just as the ancients realized that moving air exerts pressure, they also recognized that its absence did something similar. The realization that sucking air out of a closed chamber creates a vacuum seems fairly obvious to any child who has ever placed a finger on top of a straw—as indeed it was to Heron. In the preface to *Pneumatika,* he wrote,

> if a light vessel with a narrow mouth be taken and applied to the lips, and the air be sucked out and discharged, the vessel will be suspended from the lips, the vacuum drawing the flesh towards it that the exhausted space may he filled. It is manifest from this that there was a continuous vacuum in the vessel. . . .

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thus producing what a modern scholar has called a "very satisfactory theory of elastic fluids."

Satisfactory to a twenty-first-century child, and a first-century mathematician, but not, unfortunately, for a whole lot of people in between. To them, the idea that space could exist absent any occupants, which seems self-evident, was evidently not, and the reason was the dead hand of the philosopher-scientist who tutored Alexandria's founder. Aristotle argued against the existence of a vacuum with unerring, though curiously inelegant, logic. His primary argument ran something like this:

1. If empty space can be measured, then it must have dimension.
2. If it has dimension, then it must be a body (this is something of a tautology: by Aristotelian definition, bodies are things that have dimension).
3. Therefore, anything moving into such a previously empty space would be occupying the same space simultaneously, and two bodies cannot do so.

More persuasive was the argument that a void is "unnecessary," that since the fundamental character of an object consists of those measurable dimensions, then a void with the same dimensions as the cup, or horse, or ship occupying it is no different from the object. One, therefore, is redundant, and since the object cannot be superfluous, the void must be.

It takes millennia to recover from that sort of unassailable logic, temptingly similar to that used in *Monty Python and the Holy Grail* to demonstrate that if a woman weighs as much as a duck, she is a witch. Aristotle's blind spot regarding the existence of a void would be inherited by a hundred generations of his adherents. Those who read the work of Heron did so through an Aristotelian scrim on which was printed, in metaphorical letters twenty feet high: NATURE ABHORS A VACUUM.

Given that, it is something of a small miracle that *Pneumatika,* and its description of vacuum, survived at all. But survive it did,

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like so many of the great works of antiquity, in an Arabic translation, until around the thirteenth century, when it first appeared in Latin. And it was another three hundred years until a really influential translation arrived, an Italian edition translated by Giovanni Batista Aleotti d'Argenta and published in 1589. Aleotti's work, and subsequent translations of his translation into German, English, and French (plus five more in Italian alone), demonstrate both the demand for and availability of the book. Aleotti, an architect and engineer, was practical enough; in his annotations to his translation of the *Pneumatika,* he mentions the difficulty of removing a ramrod from a cannon with its touchhole covered because of the pressure of air against the vacuum therefore created—a phenomenon that could only exist if air were compressible and vacuum possible. It is testimony to the weight of formal logic that even with the evidence in front of his nose, Aleotti was still intellectually unable to deny his Aristotle.

If Aleotti was unaware of the implications of Heron's observations, he was indefatigable in promoting them, and by the seventeenth century, it can, with a wink, be said that *Pneumatika* was very much in the air, in large part because of the Renaissance enthusiasm for duplicating natural phenomena by mechanical means, the era's reflexive admiration for the achievements of Greek antiquity. The scientist and philosopher Blaise Pascal (who modeled his calculator, the Pascaline, on an invention of Heron's) mentioned it in *D'esprit géometrique,* as did the Oxford scholar Robert Burton in his masterpiece, *Anatomy of Melancholy:* "What is so intricate, and pleasing as to peruse . . . Hero Alexandrinus' work on the air engine." But nowhere was Aleotti's translation more popular than the city-state of Firenze, or Florence.

Florence, in the year 1641, had been essentially the private fief of the Medici family for two centuries. The city, ground zero for both the Renaissance and the Scientific Revolution, was also where Galileo Galilei had chosen to live out the sentence imposed by the Inquisition for his heretical writings that argued that the earth revolved around the sun. Galileo was seventy years old and living in a villa in Arcetri, in the hills above the city,

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when he read a book on the physics of movement titled *De motu* (sometimes *Trattato del Moto*) and summoned its author, Evangelista Torricelli, a mathematician then living in Rome. Torricelli, whose admiration for Galileo was practically without limit, decamped in time not only to spend the last three months of the great man's life at his side, but to succeed him as professor of mathematics at the Florentine Academy. There he would make a number of important contributions to both the calculus and fluid mechanics. In 1643, he discovered a core truth in the behavior of liquids in motion, known as Torricelli's theorem, that is still used to calculate the speed of a fluid when it exits the vessel that contains it. He made fundamental contributions to the development of the calculus, and to the geometry of the cycloid (the path described by a point on a rolling wheel). Less typically, he embarked on a series of investigations whose results were, literally, revolutionary.

In those investigations, Torricelli used a tool even more powerful than his well-cultivated talent for mathematical logic: He did experiments. At the behest of one of his patrons, the Grand Duke of Tuscany, whose engineers were unable to build a sufficiently powerful pump, Torricelli designed a series of apparatuses to test the limits of the action of contemporary water pumps. In spring of 1644, Torricelli filled a narrow, four-foot-long glass tube with mercury—a far heavier fluid than water—inverted it in a basin of mercury, sealing the tube's top, and documented that while the mercury did not pour out, it did leave a space at the closed top of the tube. He reasoned that since nothing could have slipped past the mercury in the tube, what occupied the top of the tube must, therefore, be nothing: a vacuum.

Even more brilliantly, Torricelli reasoned, and then demonstrated, that the amount of space at the top of the tube varied at different times of the day and month. The only explanation that accounted for his observations was that the variance was caused by the pressure of air; the more pressure on the open reservoir of mercury at the base of the tube, the higher the mercury rose within. Torricelli had not only invented, more or less accidentally,

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the first barometer; he had demonstrated the existence of air pressure, writing to his colleague Michelangelo Ricci, “I have already called attention to certain philosophical experiments that are in progress . . . relating to vacuum, designed not just to make a vacuum but to make an instrument which will exhibit changes in the atmosphere . . . we live submerged at the bottom of an ocean of air. . . .”

Torricelli was not, even by the standards of his day, a terribly ambitious inventor. When faced with hostility from religious authorities and other traditionalists who believed, correctly, that his discovery was a direct shot at the Aristotelian world, he happily returned to his beloved cycloids, the latest traveler to find himself on the wrong side of the boundary line between science and technology.

But by then it no longer mattered if Torricelli was willing to leave the messiness of physics for the perfection of mathematics; vacuum would keep mercury in the bottle, but the genie was already out. Nature might have found vacuum repugnant for two thousand years, but Europe was about to embrace it.

ON NOVEMBER 20, 1602, in Magdeburg, a town in Lower Saxony, hard by the Elbe River, the former Anna von Zweidorff, by then the wife of a prosperous landowner named Hans Gericke, gave birth to a son, Otto. This was something like being born in Mogadishu, Somalia, in 1975: When Otto was sixteen years old, the armies of the last great religious war in European history began marching and countermarching across Germany, enforcing orthodoxy at the end of a pike in what became known as the Thirty Years War. Magdeburg, which had been a bastion of Protestantism ever since Martin Luther had visited in 1524, became a target for the armies of the Catholic League, not once, but half a dozen times; in 1631, the troops of Count Johann Tilly sacked the city, killing more than twenty thousand. By the time the various treaties that comprised the Peace of Westphalia were signed in 1648, the city was home to fewer than five hundred war-weary

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survivors. One of them was Otto Gericke, home from his studies in Leipzig, Jena, and Leiden, now a military engineer who was enlisted to help rebuild the city, and had been named one of its four mayors. He was, entirely as one might expect, eager to turn his talents to more peaceful pursuits.

Though evidently unaware of the details of Torricelli's experiments, he was headed down the same path, intending to demonstrate the power of a vacuum and therefore the weight of air. By 1650 or so, he had built the *Magdeburger windbüchse,* which looked like a gun but worked like a vacuum pump, a piston encased in a cylinder with an ingenious one-way flap valve that kept the cylinder airtight once the piston was withdrawn and was rightly regarded as one of the "technical wonders of its time." It was, however, barely an appetizer for what came next. For in 1652, Gericke, fascinated by the elasticity and compressibility of air, was to produce some of the most famous experimental apparatuses in history.

The original copper objects that came to be known as the Magdeburg hemispheres are on view at the Deutsches Museum in Munich, looking today a bit like oversized and battered World War I army helmets, with a dark bronze patina caused by nearly four hundred years of oxidation. Ropes dangle from half a dozen iron fasteners on both, and one holds a tube designed to mate with Gericke's vacuum pump. When Gericke constructed them in 1654, the ropes were tied to the harnesses of a team of horses, and the copper shone like a mirror. The reasons had more to do with theater than science. With the smooth rims of the hemispheres coated with grease, the air pumped out of the globe, and the horses urged in opposite directions, the show was irresistible. Its first appearance was in 1654, in front of the Imperial Diet in Regensburg, where Gericke tied his ropes to thirty horses—fifteen attached to either hemisphere—and demonstrated their inability to pull the pieces apart. That was followed by similar entertainments in 1656 in Magdeburg (with sixteen horses), in 1657 before the emperor's court in Vienna, and most famously of all, in 1664, before the German elector Friedrich Wilhelm, who was amazed to

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see twenty-four horses straining to pull apart a twenty-inch globe held together only by air pressure.*

The Magdeburg hemispheres are deservedly some of the most famous experimental devices of all time, and versions are still used in science classrooms to this day. But their fame owes at least as much to showmanship as to any intrinsic contribution to the physics of vacuum. In 1661, Gericke performed a far more sophisticated, though less well remembered, experiment. It consisted of two suspended platforms connected by a single rope, each under a pulley, with both pulleys suspended from a horizontal beam. On one he placed an airtight chamber with a close-fitting piston; on the other, a measured amount of lead weight. As the air was pumped out of the chamber, the piston was forced down by the weight of atmosphere, and the weight raised by the same amount—the first practical application of the power of the vacuum, well recounted in his 1672 book, *Experimenta nova, ut vocantur, Magdeburgica de vacuo spatio.*

But it was the hemispheres that, in the end, mattered. They are the reason Emperor Leopold I knighted Gericke in 1666, making him Otto von Guericke (including the unexplained introduction of the *u* to his name). It was the hemispheres that a German Jesuit and mathematician named Gaspar Schott saw at the 1654 demonstration, and that initiated an admiring correspondence between Schott and Gericke. And it was the hemispheres that were featured in Schott's 1657 book, with the intimidating title *Mechanicahydraulica-pneumatica,* which contained a description of both the vacuum pump and the hemispheres (and included a drawing eerily similar to the logo used by Levi Strauss to testify to the inability of even whipped horses to pull a pair of jeans apart). And of course the hemispheres mark another fork in the road for the idea powering engine 42B on its way from conti-

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* Part of the story of the Magdeburg hemispheres remains a bit of a mystery. Even if Gericke had been able to achieve a perfect vacuum—unlikely, with the equipment he had at hand—the total air pressure at sea level on a globe twenty inches in diameter would be a bit less than five thousand pounds—a lot, but not too much for thirty horses.

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nental Europe to Britain, where Schott's book traveled almost as soon as it was published.

ENGLAND, IN THE MIDDLE of the seventeenth century, had not witnessed the brutal devastation that had been visited upon Gericke's homeland by the Thirty Years War, but it had not exactly been a model of peaceful coexistence either. A dispute between King and Parliament over their respective degrees of authority exploded into civil war in 1643; it had been temporarily suspended by the execution of Charles I and the exile of his son, Charles II, but not before a hundred thousand men, women, and children were dead. One of the Civil War's less dramatic but equally far-reaching consequences was that the various colleges at Oxford, which had been the king's base of operations for much of the war, had walked a delicate line between their traditional and reflexive support for the monarchy and prudent obedience to its replacements: first the Commonwealth, and then the de facto dictatorship of Oliver Cromwell. By the time England, and Oxford, had received copies of Schott's book, they had been without a king for years, and the town's scholars, two in particular, were more interested in persuading nature to give up her secrets than in forcing their countrymen to choose a sovereign.

It seems almost indecently apt that Robert Hooke and Robert Boyle were among the first, and certainly the most important, men in England to learn of Gericke's experiments. The aptness is not due entirely to their interest in vacuum; these wildly inventive, almost ridiculously prolific men were interested in practically everything. A brief list of their respective achievements would include the discovery of the Law of Elasticity; the founding of the science of experimental chemistry; the invention of the microscope; the discovery of the basic law governing the behavior of gases; the first observation of the rotation of both Jupiter and Mars; the discovery of the inverse-square law of gravity; the authorship of some of the seventeenth century's most profound Christian apologetics; and the founding of the world's first scientific society.

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Their link began in 1659 or so, when Boyle, a brilliant and wealthy aristocrat, hired Hooke, a brilliant and impecunious scholarship student, to improve on Gericke's vacuum pump. The improvement that Boyle had in mind was critical: He needed a machine that would not merely demonstrate the existence of a vacuum for the entertainment of European aristocrats, but would allow him to investigate its characteristics. Hooke's answer was the *machine Boyleana,* an experimental device that would reveal what was happening inside the vacuum chamber and allow manipulation of it. Boyle had earlier hired the now forgotten Ralph Greatorex ("the leading pumping engineer in England") to achieve these goals, but where he had failed, Hooke succeeded. His design incorporated a glass vessel and two cone-shaped brass stoppers that, when coated with oil, could be rotated, pulling a thread that could be attached to the clapper of a bell, the wick of a candle—to anything, in short, that might be part of a viable experiment on the nature of vacuum.

All by itself, Hooke and Boyle's series of vacuum experiments, described in the 1660 publication of *New Experiments Physico-Mechanical, Touching the Spring of the Air and Its Effects,* would have bought them an entry in the history of steam power. In their hands, the machine Boyleana made basic discoveries into the properties of sound—when air was removed from the chamber, so too was the sound of a bell within it—of animal respiration, and of combustion. The experiments conducted by the two men produced the law of physics that still bears Boyle's name,* and the demonstration that the volume of a gas at constant temperature is inversely proportional to pressure (with the corollary that increasing temperature equals increased pressure) is an insight of some significance for the road leading from Torricelli's mercury tube to engine 42B.

However, the most significant characteristic of the two men's work—the one that best reveals why the road to steam power was

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* Though it should be noted that in 1676, the French physicist and priest Edmé Mariotte independently discovered "Boyle's" law, and that in many European countries, the same equation is known as Mariotte's Law.

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thereafter almost entirely an English one—is the fact that Boyle hired Hooke.

BEGIN WITH THEIR BEGINNINGS: Robert Boyle was one of the younger sons of an earl, born in Lismore Castle and educated at Eton, in Switzerland, and in France. By the time he returned from Florence in 1642 (where he read Galileo's *Dialogue on the Two Chief World Systems* and began a lifelong devotion to mechanical explanations: in his words "those two grand and most catholic principles, matter and motion"), his father had died, leaving him a Dorsetshire manor and sufficient income from his Irish estates to study whatever part of "matter and motion" took his fancy. Hooke was born to a modest curate on the Isle of Wight, who left him just enough to purchase an apprenticeship with a portrait painter. Boyle arrived in Oxford in 1654 as a gentleman scholar; Hooke made his way to Oxford a year later, a scholarship student eager for anything to supplement his very modest stipend.

The two did share an affinity for the royalist cause, though not especially for the High Anglicanism associated with it. Boyle, in particular, was a devoted Protestant, well remembered for his piety, who famously argued (in *The Christian Virtuoso*) that devoutness did not forbid study of natural phenomena, but rather demanded it. His advocacy of experiment and experience—in brief, empiricism—as the best method for explaining the world was partly a response to the materialism (halfway to atheism, in the view of Boyle's Oxford colleague, Seth Ward) of Thomas Hobbes, who returned the favor, sneering at Boyle's work, which he called "engine philosophy."

Robert Hooke's philosophy, on the other hand, seems to have been driven more by a need for recognition than salvation. For all his extraordinary range of achievements (not only was he Christopher Wren's surveyor and colleague during the rebuilding of London after the Great Fire of 1666, an early advocate of evolutionary theory, the first to see that organic matter was made up of the building blocks that he named "cells," and probably England's

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most gifted mathematician, able to turn his hand to everything from describing the catenary curve of the ideal arch to the best way to trim sails), he is frequently remembered today, as he was known during his lifetime, as the world's best second fiddle. The shadow cast by Wren, by Boyle, and even by Isaac Newton, with whom Hooke engaged in a long-running and ultimately futile dispute over the authorship of the law of gravitational attraction, is unaccountable without considering the class difference between them. James Aubrey, the seventeenth-century memoirist, paid Hooke something of a backhanded compliment when he called him "the best Mechanick this day in the world."

When the informal assembly at Oxford whose meetings were generally led by the clergyman John Wilkins was chartered, two years after the Restoration of Charles II in 1660, as the Royal Society of London for the Improvement of Natural Knowledge, each Fellow was explicitly to be a "*Gentleman*, free, and unconfin'd." Hooke's need to make a living disqualified him from fellowship, though his talent made him indispensable. The solution—he was appointed to the salaried position of curator of experiments for the Royal Society in 1662—made him the first scientist in British history to receive a salary, though the salary in question was long in coming. It took until 1665, when Hooke was appointed professor of geometry at Gresham College at an annual stipend of £50 for life; the Royal Society then coughed up another £30, to make good on their original promise to Hooke of £80 a year.

Robert Hooke's pioneer status makes him a persuasive bridge between technology and science, which was in 1665—and for decades thereafter, in Britain and everywhere else—still the province of amateurs. Hooke spent his life in an occasionally successful search for both recognition and recompense, attempting, among other things, to turn his Law of Elasticity into ownership of the watch escapement, whose spring-loaded movement was a direct outgrowth of the Law.* When he died, his frugally ap-

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* Tellingly, in order to keep his discovery secret, and so secure his status as its discoverer, he first published the Law in the form of an anagram.

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pointed apartments contained a considerable amount of cash, largely earned from his surveying, contributing to a probably false reputation as a bit of a miser, but his attitude toward invention seems to be, in its way, as significant an innovation as his vacuum pump.

While Boyle is traditionally remembered as the more important transitional figure in the development of steam power, he exhibited a strong prejudice in favor of those whose experiments were entirely in service of the search for truth, as opposed to those "mere Empiricks" and "vulgar chemists" simply trying to "produce effects." This distinction makes his position clear in the never-ending debate between pure and applied science—really, between science and invention—that was already thousands of years old by Boyle's day.

The debate continues into our own day. Which is why it is Robert Hooke's life, rather than Boyle's, that leads from Torricelli (whose promising start on the potential uses of vacuum were forestalled by conservative Aristotelianism) and von Guericke (whose undoubted talent for innovation is mostly remembered as a circus act) on the path to engine 42B, and to *Rocket.*

The next steps on that path would take the technology of steam and vacuum irrevocably into the world of commerce.

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CHAPTER TWO

A GREAT COMPANY OF MEN

concerning the many uses of a piston; how the world's first scientific society was founded at a college with no students; and the inspirational value of armories, Nonconformist preachers, incomplete patterns, and snifting valves

MIDWAY ALONG A LINE of statues that overlooks I. M. Pei's glass pyramid at the Louvre, near the images of René Descartes and Voltaire, a rather forbidding figure looks down on the Napoleon Court. The man's right hand, as is traditional, is tucked into his coat. His left hand, however, holds a curious contraption, something that looks a bit like a plumber's helper but is in fact one of history's most important leaps of mechanical imagination: the world's first steam-driven piston. The hand holding it belongs to its inventor, Denis Papin, whose ingenuity was critical to the creation of a steam-powered world, and whose life illustrates, as well as anyone's, the challenges of the inventive life.

The son of a government official in the city of Blois, Papin, a Huguenot (like many in the city, which had long been a haven for French Calvinists), was trained as a physician at the University of Angers and possibly even practiced as one for a few years, though his later comments suggest he much preferred physics. In 1671, he

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got the chance to act on that preference when he met the Dutch mathematician and physicist Christiaan Huygens, a founding member of the Académie des Sciences (inaugurated in 1666 as the French equivalent of the Royal Society), who was at Versailles repairing a balky windmill used to power the palace's fountains. The following year, Huygens, who had been impressed with Papin's mechanical insights, offered him a job as his secretary, and Papin gave up the healing arts for good, migrating to Paris to work at the Royal Library.

Huygens was another in a seemingly unending line of seventeenth-century scientists fascinated by vacuum and atmospheric pressure, and Papin's time with him was evidently both satisfying and productive. The two worked on a number of air pump experiments, and jointly published five papers in the *Philosophical Transactions* of the Académie Royale in 1675, though histories differ on whether they worked together on Huygens's gunpowder-driven piston, a promising but slightly hazardous technology.

During Papin's stay in Paris, life in France was becoming more than slightly hazardous for the nation's Huguenots, the beginning of a process that would end in the revocation of the Edict of Nantes and the return of official persecution, in 1685. By then, Papin had accurately read the writing on the wall, and, seeing no future for him in his birth nation, crossed to England in the fall of 1675. He was armed with a letter of introduction from Huygens to Robert Boyle, who was in need of a collaborator to replace Hooke, whose own researches were by then being financed by his employers at Gresham College and the Royal Society. The two evidently hit it off, and Papin joined Boyle as his secretary, though a better term would have been "experimental assistant."

While Papin was no Hooke (this is scarcely an insult: by 1675, Hooke had explained the twinkling of stars, described the earth's elliptical orbit, rebuilt the fire-destroyed Royal College of Physicians, disputed with Sir Isaac Newton over the discovery of the diffraction of light, and invented the anemometer, and he still had twenty productive years in front of him), he did excel at both experimental design and mechanical gadgetry. Most famously, in

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1681 he invented a steam digester, or "machine for softening bones" as he described it, which was essentially a pressure cooker designed to clean bones rapidly for medical study.

The subsequent pattern of Papin's life would be familiar to any contemporary academic in search of a tenure-track position. In 1679, before the steam digester made him briefly famous, Papin was hired by his predecessor, Robert Hooke, as a secretary at the Royal Society at an annual salary of £20; he left there in 1681 for a new job as "director of experiments" at the Accademia Publicca di Scienze in Venice, yet another Royal Society imitator. After the Accademia failed, Papin returned to England, and Hooke, for three more years, this time as "Temporary Curator of Experiments" at the Royal Society, leaving *that* to become professor of mathematics at the University of Marburg.

Papin's contributions might have had an even larger impact had he enjoyed, like Boyle, the income from lands acquired by the Earl of Cork. And they are not small even so. In the 1686 issue of *Philosophical Transactions,* Papin describes (though evidently did not actually construct) an early air gun, probably a direct outgrowth of his gunpowder-piston experiments with his onetime mentor, Huygens. His digester featured a brilliantly innovative safety valve: When the pressure inside the chamber of Papin's invention grew high enough, it would overcome the weight of a hinged and weighted stopper and open a path to the outside, but when the pressure subsided, the stopper's weight would cause it to sink back to its normal position.

Most significantly for the evolution of the steam engine, in 1690 he published, in the *Acta Eruditorum* of Leipzig, a design of a true atmospheric engine: one that used the vacuum created by steam condensation to let atmospheric pressure drive a piston—the same one carried by his statue at the Louvre. Papin's great insight was recognizing that the weight of the atmosphere on the top of an open cylinder, which is apparent only when a vacuum is created at the cylinder's bottom, could also drive something mechanical *within* the cylinder. He wrote, "Since it is a property of water that a small quantity of it turned into vapour by heat has an

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elastic force like that of air, but upon cold supervening is again resolved in water, so that no trace of the said elastic force remains, I conclude that machines could be constructed wherein water, by the help of no very intense heat, and at little cost, could produce that perfect vacuum which could by no means be obtained by gunpowder."

By 1707, he was corresponding with Gottfried Wilhelm Leibniz, the German mathematician, engineer, and philosopher,* about the possibilities of an engine driven by steam pressure, all while trying to keep his head above water as a poorly paid councillor to Charles-August, Landgrave of Hesse-Kassel, a German principality located on the Prussian border. Keeping the landgrave interested proved a challenge all its own: Papin built him a centrifugal pump (evidently to water the landgrave's gardens) and a furnace air blower that became known as the "Hessian bellows." He even tried to design a hydraulic perpetual motion machine based on the belief that pressure from one large cylinder would provide a never-ending source of pressure on a smaller cylinder. By the time he built a demonstration submarine for his patron, however, the landgrave had already lost interest in it, and in Papin, who returned to England for the final time, spending his last years in unsuccessful attempts to promote a pension from the Royal Society and dying in poverty in 1712.

Papin was by all accounts a difficult man who lived a difficult life, and it is impossible to tell which was cause and which effect. He spent virtually all his adult years as a refugee, partly because of his religion—the late seventeenth century was no time to be a French Protestant—but even more because he was enormously rich in talents for which no market yet existed. He was an industrial scientist before there was an industry to employ him, which made him, in consequence, completely dependent on patronage.

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* It is impossible to do justice to Leibniz with anything less than a full biography. He was simultaneously one of the greatest mathematicians and philosophers of the eighteenth century, with a list of achievements ranging from the calculus (the notation we use today is his, not Isaac Newton's) and binary logic to metaphysics, philology, and both basic and highly speculative physics.

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His correspondence is evenly divided between generous sharing of his scientific discoveries and pleas for pensions, the latter wearing out his welcome in half a dozen countries. Papin's career, even more than Hooke's, illustrates the challenges faced by the most talented scientists if they lacked an independent source of income. The archetype—innovative talent supported either by patronage (governmental or aristocratic) or by inheritance—was as old as humanity and still quite sturdy.

Before he became an object lesson in the difficulties of making a living as a seventeenth-century inventor, however, Papin made one final connection on the route to engine 42B, and to *Rocket.* In 1705, Leibniz, then a courtier in the north German city of Hanover, received a sketch of a new machine for using steam to raise water, which he immediately sent to Papin in Hesse. The sketch had come from London.

THE TALLEST SKYSCRAPER IN the City of London, known variously as Tower 42 and NatWest Tower, occupies a site in Bishopsgate that was the former home of what was once London's only university: Gresham College, founded by a bequest from the will of Sir Thomas Gresham as a sort of scholarly Shangri-La, a college with neither students nor degrees. Instead, it houses scholars who offer lectures to any member of the public who cares to attend, and has been doing so ever since 1597. When Christopher Wren was tapped, in 1660, for the first lecture to what was to become the Royal Society, he was the Gresham Professor of Astronomy, and consequently that was where the lecture was given. The Royal Society called Gresham home for the next forty years, except for a brief period when fire and plague chased them out of London altogether.

Thus it was at Gresham College on June 14, 1699, that the Royal Society assembled for a demonstration of what was described as "a new Invention for Raiseing of Water and occasioning Motion to all Sorts of Mill Work by the Impellent Force of Fire which will be of great use and Advantage for Drayning Mines"—

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