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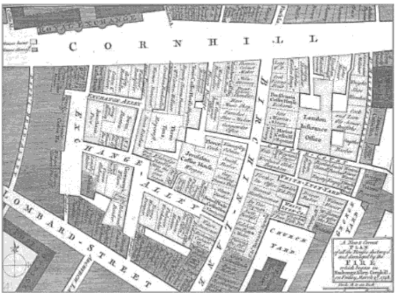
INTRODUCTION
“the great Follies of Life”

LONDON, 1719

The year had begun well enough for London’s stock traders, working from their corner of the city, a narrow passage called Exchange Alley. Buying and selling shares—dealing not in things but in numbers—was still new to the city. There was no fixed marketplace for traders in paper. So those who had mastered what was to many still a very dark art concentrated in a few taverns and inns, at Garraway’s, a coffeehouse that catered to the gentry, and more of them just around the corner at Jonathan’s, the rival coffeehouse that saw the most feverish trade in all the new ways in which it was possible to make—or *be*—money.



Exchange Alley in its early-eighteenth-century layout

For journalist, propagandist, and gadfly Daniel Defoe, Jonathan’s and the rest were familiar—and dangerous: dens of iniquity. Defoe had been warning his fellow Britons about the perils of the Alley for almost three decades. Now, near midsummer, he was ready with his most desperate alarm yet, a pamphlet titled *The Anatomy of Exchange Alley,* written in the voice of "a jobber," or unlicensed dealer in stocks. In part, the pamphlet served as a kind of travel story, leading its readers on a journey to an exotic spot. Exchange Alley was an island in miniature. It could be walked in a minute or two: "Stepping out of Jonathan's [Coffeehouse] into the Alley, you turn your Face full *South,* moving on a few Paces, and then turning Due *East,* you advance to *Garraway*'s; from thence going out at the other Door, you go on still *East* into *Birchin-Lane,* and then halting a little at the Sword-Blade Bank to do much Mischief in fewest Words, you immediately face to the *North,* enter *Cornhill,* visit two or three petty Provinces there in your way *West.*" There, a few hundred paces at most, and the visitor would be almost done: "Having Box'd your Compass, and sail'd round the whole Stock-jobbing Globe, you turn into *Jonathan*'s again." Home again!—but not in safe harbor, for the jobber concludes that "as most of the great Follies of Life oblige us to do, you end just where you began."

And what folly it was! Defoe painted the risk faced by any reckless soul foolish enough to wander into Jonathan's, in the tale of a naïvely avaricious countryman who encounters a couple of con men. They ply him with rumors, urge him to trade on their insider's knowledge, and surgically extract his entire fortune: "his Coach and Horses, his fine Seat and rich Furniture," all sold "to make good the Deficiency."

That was typical of Exchange Alley, Defoe warned his readers. It fostered "a compleat System of Knavery...a Trade founded in Fraud." Its tricks were hardly new, of course. In some form, they're as old as human desire, as the book of Proverbs attests: "The getting of treasures by a lying tongue is a vanity tossed to and fro of them that seek death." But this hopeful, nervous year of 1719 held something new, a scheme more ambitious than anything previous attempted by the devilish denizens of the Alley. The South Sea Company had opened for business in 1711. The firm had never really managed to do the work implied by its name, shipping goods and slaves to the Spanish ports of South America. Instead, it played in what was then just being born, a marketplace for credit, all the notes and bonds and much stranger inventions that the British government was using to build its ever-growing mountain of debt. For several years, the South Sea Company itself had nibbled around the edges of this market, completing a handful of minor deals, but its directors now aimed at a vastly more ambitious project—one that would, if it worked, solve Britain's borrowing problem once and for all. They proposed a heroic attempt at what we would now call financial engineering—taking the whole of the national debt, accumulated over a seemingly endless series of wars, and turning it into shares of a private company—theirs—which could be traded back and forth at will in the nascent stock exchange. In its partisans' view, that would be the saving of the nation. Alternatively, as the skeptical Defoe warned, the clever men of Exchange Alley had figured out a way to get rich off of the public interest: they were "ready, as Occasion offers, and Profit presents, to Stock-jobb [buy and sell] the Nation, couzen [trick] the Parliament, ruffle the Bank, run up and run down Stocks, and put the Dice upon the whole Town."

"Stock-jobb the nation." That was the crux of Defoe's polemic: schemes like this transformed the national debt—a public necessity—into a form that could be manipulated for private profit. That was, he argued, if not treason itself, then treachery's nearest cousin: "Is not all that is taken from the Credit of the Publick, on such an Occasion…is not every Step that is taken in Prejudice of the King's Interest…a plain constructive Treason in the Consequences of it?"

In the most straightforward account of the events that were to come—known to history as the South Sea Bubble—Defoe would be proved right. In the year 1720, every Briton with two shillings to rub together, it seemed, would hear of the South Sea Company, would buy into its promises, and would be dazzled, for a time, at the prospect of riches beyond imagining. Half of Europe would too, and for a very great many it would end in ruin.

AND YET, SEEN with enough distance (and a comfortable remove from those lost fortunes), it's clear that Daniel Defoe was also wrong. What would happen in Exchange Alley over the next year wasn't simply the work of "a Trade founded in Fraud, born of Deceit, and nourished by Trick, Cheat, Wheedle, Forgeries, Falshoods." The South Sea Bubble—the headlong rise and the sudden collapse of London's nascent stock market—wasn't the original sin of early modern capitalism—or rather, it was never only that.

Instead, as this book argues, if we are to understand the Bubble year, wider histories must come into play, ones that reach both backward and forward in time, from Defoe's troubled days to our own. In this telling, the calamities of 1720 can be read as a watershed moment in the long, tangled process of creating the modern concept of money, and especially of money's most dynamic incarnation, credit—which makes promises expressed in numbers that connect the future to the present. The Bubble is a part of the history of finance but is not confined to it. Rather, it opens a window on the circumstances from which later financial thinking emerged: the grand shift over the preceding century in the way human beings understood their experience of the material world, an intellectual transformation better known as the scientific revolution.

The history of the scientific revolution is usually told as a sequence of discoveries, mostly in mathematics and physics. That picture leaves out a central human fact: those who solved problems of planetary motion or the flight of cannonballs did not confine themselves to natural philosophy. From the beginning, they used the same methods and habits of mind to tackle human questions, to guide the choices made by individuals and societies. In 1719, on the brink of the wild ride to come, the greatest revolutionary of them all worked just a few hundred yards to the southeast of Exchange Alley. There, in rooms built along the outer wall of the Tower of London, Sir Isaac Newton, master of the Royal Mint, produced Britain's supply of the "real" money: gold and silver bullion of precisely defined and authenticated purity, rolled and punched and stamped into disks of legally mandated weight, decorated with the head of the king. He'd been advising the crown on monetary matters since the mid-1690s, and by this time he was an experienced stock market player on his own account—which included, at this moment, a tidy sum in South Sea stock. The year to come would test him as much as anyone else—but his significance to the events of 1720 lies in the way he taught his contemporaries to think, not just about money, but about anything that could be observed, measured, and counted.

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THE CATASTROPHE NOW known as the South Sea Bubble is on record as the first and in many ways the archetypal stock market crash and fraud. What happened then and what the British state did in response both have a direct connection to what has occurred (and may soon come again) in the financial life of the twenty-first century. In the moment, it certainly proved Defoe's point about the significant threat that arises when the motives and interests of the financial elite clash with those of national governments and the public. And certainly, pawing through the wreckage left after the Bubble burst uncovered an extraordinary catalog of corruption, a comprehensive guide to all the ways it's possible to subvert the market for private gain.

But to understand how the nation got itself into the Bubble, and to grasp what actually had occurred behind the surface of catastrophe, we must follow the story further back in time—to a garden, an orchard. There waits the young Isaac Newton, a man barely past boyhood. He can see an apple tree, laden at this midsummer moment with fruit—a variety called Flower of Kent.

At any moment, one might fall.

PART ONE

COUNTING AND THINKING

Natural Philosophy consists in discovering the frame and operations of Nature, and reducing them, as far as may be, to general Rules or Laws,—establishing these rules by observations and experiments, and thence deducing the cause and effects of things.

—ISAAC NEWTON

Chapter One
"The System of the World"

WOOLSTHORPE, LINCOLNSHIRE, MIDSUMMER, 1665

He had walked for three days to escape a farmer's life just four years before. There'd been no hint he'd ever return. Yet, here he was again, about to open the gate. Little had changed: the main house, stone-built, comfortable; the barn behind; and, just across the track from the front door, the little patch of garden with its stand of apple trees, warming in the early-summer sun. He'd been nineteen when he left, a country boy, awkward and unsociable, much given to scribbling in his notebook. He was twenty-three now and had a place in the world: a scholar of Trinity College, Cambridge, with rooms and a stipend and his own place at table. But now, smack in the middle of term, he was coming up the lane, crossing to the door, and stepping over the threshold, into the house.

Isaac Newton had come home.

Or rather, he had been chased back to Woolsthorpe's quiet corner of the Lincolnshire countryside. Cambridge had been emptying since late spring, as each of its seven thousand or so residents who had anywhere to go desperately fled the approaching danger. That threat had been carried in its turn by those coming up the roads from London, on the run from the terror that had already reached the capital.

No one knows precisely how the plague reached London in the early months of 1665. Attentive observers had been nervous throughout 1664. The diarist and navy bureaucrat Samuel Pepys kept his eyes on Amsterdam, where a full-blown epidemic had begun in the previous fall. Pepys first took note of the danger in October, and then in November recorded in his diary that ships coming from infected ports now faced quarantine along the Thames. But some still arrived, smugglers carrying cloth, or, after the new year, with the start of the second Anglo-Dutch War, vessels bringing prisoners home. There were always rats on board, and rats carry fleas. Fleas host the *Yersinia pestis* bacterium.

Y. pestis causes the plague.

Winter came, the slowest season for infection. For a time, it appeared that England might escape the scourge suffered on the other side of the North Sea. A few cases were reported. The bill of mortality for the crowded parish of St. Giles in the Fields records one plague death on Christmas Eve, 1664—a "Goodwoman Phillips." When she fell ill, Phillips, her husband, and their unnamed and unnumbered children were placed in quarantine, and their home was shuttered, guarded, and bedaubed with the plea "Lord Have Mercy on Us." But the infection apparently stopped there, and the next weeks were quiet. Plague was endemic in England, and every year saw a few come down with the disease. This appeared to be just one more case, and not the first of a new tidal wave of infection.

The winter ended, and spring began kindly. Two more plague deaths show up in London's weekly bills of mortality in the last week of April, again in St. Giles in the Fields. The first week in May saw none...but then the numbers turned. Nine in the second week, three in the third. Fourteen for the week of May 23. Seventeen reported on the thirtieth. Forty-three on June 6—and the tally leapt from there. The official record topped a thousand on July 28, then doubled, and doubled again. By September, one thousand Londoners were dying each day. By year's end, the official toll would approach seventy thousand, as many as one in eight of the city's residents.

Everyone who could get out of town did. On June 21, the ubiquitous Pepys, secretary to the Admiralty, had a meeting in Whitehall, trying to unravel King Charles II's perpetual money troubles. Achieving nothing more than usual, he set out across the city to Cripplegate, one of the ancient openings in London's city wall. There, he recorded in his diary, he found "all the towne almost going out of towne, the coaches and waggons being all full of people going into the country." He stopped awhile at the Cross Keys tavern—long enough to enjoy the company of the barman's wife—but by the next day he was ready to decide "whether to send my mother into the country today." She didn't want to go, but "because of the sicknesse in the towne, and my intentions of removing my wife," he finally managed to put her on a coach that would take her east, toward Cambridgeshire.

London's exodus had the predictable result: refugees from the capital carried the contagion into the countryside. Some towns barred their gates to keep the disease at bay. It didn't work. In Cambridge, the blow fell on July 25. John Morley, five years old, was found dead at his home in the parish of the Holy Trinity. There were dark spots on his chest. When the plague inspectors came, they found Morley's younger brother already showing black irruptions on his face. The child was taken to the pesthouse, where he died ten days later.

Ann Fisher, a child from All Saints Parish, died on the same day, confirming that the disease had spread beyond a single neighborhood. More cases followed, more deaths, and from there Cambridge followed London's pattern. Businesses shuttered. Stourbridge Fair, one of the greatest open-air markets in Europe, was canceled. The university scattered. On August 7, the College of the Holy and Undivided Trinity acknowledged the obvious and decided to pay its members an allowance whether or not they remained in residence after that date. No record for Isaac Newton appears in Trinity College's accounts for the extra stipend. The newly passed bachelor of arts had already fled, traveling the sixty miles north and a little west to Woolsthorpe.

—

THERE HE REMAINED for almost two years, cut off from every other scholar or mathematician. The isolation suited him. "In those days," he would recall half a century later, "I was in the prime of my age for invention & minded Mathematics & Philosophy more than at any time since."

Those twenty months are now known as Newton's *annus mirabilis*—his miracle year. In that brief time, he would solve several problems at the leading edge of contemporary mathematics. The decks thus cleared, he would go on to invent whole new ideas, laying the foundations of what we now call calculus, the mathematical tool used to analyze (among much else) change over time—where a cannonball might be at any instant, or a planet, for example. He then turned to what we now call physics, beginning with mechanics, the study of bodies in motion. Here too, before he could uncover specific results he had to work out fundamental concepts, mastering the first modern understanding of inertia, for example, an idea he first encountered in Descartes's work, and thinking deeply about what it means to be a force—two ideas so essential to the future development of our understanding of the physical world that he in large measure had to construct them himself before he could go any further. Then came the first glimpses of what would become his theory of gravity and all that flowed from that epiphany. And, still not done, he dove further into an investigation of light, color, and optics that would yield his first great public triumphs. The record does not reveal when—or whether—Isaac Newton slept.

This seemingly superhuman accumulation of ideas during his plague-imposed exile has created a mythology of superhuman genius, conjuring worlds of thought out of country air. It's not quite that simple, of course. Newton's definitive biographer, Richard Westfall, points out that the program for the work to come was laid down in 1664, when Newton, just twenty-one, was still enrolled at Trinity College. That's when he first dove into the mathematical inquiries that would dominate his first several months back home, and when he produced an extraordinary series of forty-five queries in which he grappled with fundamental issues of time, matter, motion, and much more. He didn't need the plague, that is, to launch him into his comprehensive assault on the whole of natural philosophy. But it is true that when he reached the farm he was ready to move beyond anything Cambridge could teach him. He was "consistently concerned," as Westfall wrote, "to develop general procedures" that would, in the end, produce not just new mathematics but a new way of thinking about how math insinuates itself throughout the material world.

One of the first problems to catch his eye was how to calculate the area marked out by a curve. The study of curves was a central fascination of seventeenth-century mathematics, and Newton had plunged into the field when he read a translation of René Descartes's *Geometry* a year before the plague hit. Descartes's approach helped link together the approach of classical geometry, which explored shapes and their properties, and the ideas of algebra, with equations whose solutions could be mapped onto a particular curve.*

One of the key advances Newton encountered in his copy of *Geometry*—the Latin translation that spread Descartes's ideas throughout learned Europe—was the coordinate system now known as Cartesian coordinates. It provided a way to map any point in two dimensions with just two numbers, corresponding to its horizontal and vertical positions. Using two lines perpendicular to each other—the familiar cross of every graph in grade school math classes—and a standard unit length applied to both axes, Descartes created a systematic way to measure and map any shape a geometer wanted to study—including the classical curves, circles, ellipses, and the rest.

When Newton came to study this work, and then more contemporary mathematics, he soon turned one of its approaches on its head. In classical geometry, the starting point for most European mathematicians, the curve or the shape is the object of inquiry. Even though Cartesian coordinates offered a new and powerful way of representing equations as shapes on his coordinate system, many of Newton's contemporaries saw such equations as a property of a given figure, a line or a circle or some more complicated form. But it took Newton just a few months after encountering Descartes to realize, as his biographer, Richard Westfall reports, "The equation is more basic than the curve; the equation defines, or as Newton put it, expresses the nature of the curve."

That sounds like a technical point, or even one of taste: some folks think in pictures and, if they are mathematical, dive into the relationships between shapes and volumes, while others play the game of manipulating those abstractions. But Newton's insight—starting first with the equation, rather than the shape—was foundational because it would, first hesitantly and then through centuries of development, yield a new way of seeing the world through mathematics. For his predecessors, the classical geometers, the curve was there, complete, a synoptic view of the object. But in Newton's work, in the early years of what is now known as analytic geometry, a curve is built up as a calculation reveals the solutions to the equations that generate any given geometrical object. The accumulation of specific answers to these calculations—points on a curve, plotted on the page to produce a geometric object—can be interpreted in various ways. The interpretation that Newton would develop focused on arguably the most important implication: equations describe the evolution of a system—how its solutions build a picture on a page. That picture is a map of the relationship of variables—things that can change. If one of those variables is the passage of one moment into the next, then the abstract play of symbols and shapes becomes a portrait of change in action.

Ultimately, this mathematical insight is at the heart of modern physics, the science that Newton, more than any other single thinker, would create. In its simplest form, the idea is this: the full picture, the complete geometrical representation of all the available solutions to a system of equations, can be understood as all the possible outcomes for a given phenomenon described by that mathematics. Each specific calculation, fed with observations of the current state of whatever you're interested in, the flight of a cannonball, the motion of a planet, how a curveball swerves, how rapidly an outbreak of the plague might spread, makes a prediction for what will happen next. In his twenties, working on his own, with almost no systematic experience of the study of the real world, Newton did not yet grasp the full power of the ideas implied by the way he had begun to think about math. That would come in time. But what made his *annus mirabilis* so miraculous was the speed and depth with which Newton forged the foundations of his ultimately revolutionary way of comprehending the world.

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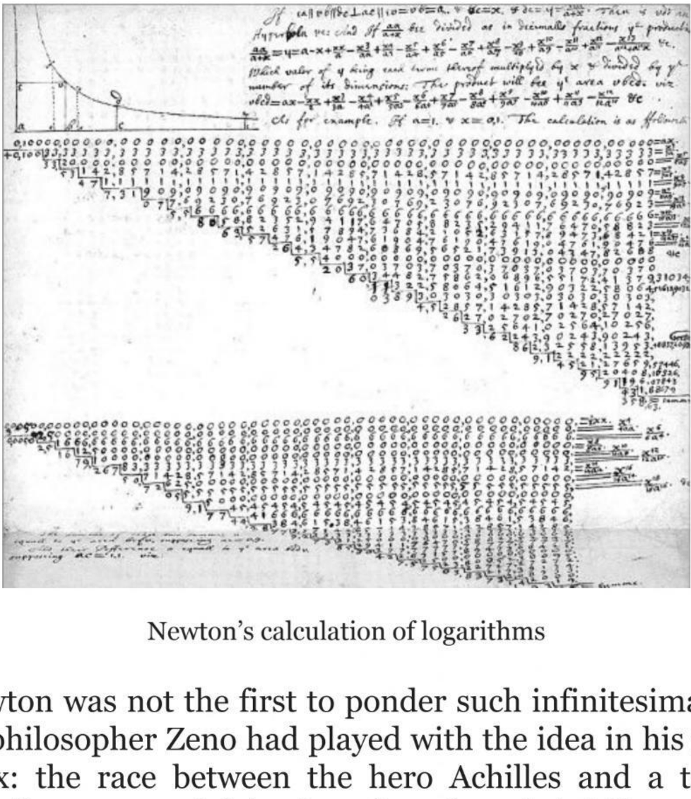
THE NEXT STEP in that revolutionary path came as Newton worked on new ways to analyze and solve mathematical problems. Only the simplest algebraic equations can be solved just by plugging in numbers and doing the arithmetic. Seventeenth-century attempts to analyze more complicated expressions often employed a particular mathematical tool, the infinite series—endless sequences of terms (for example, 1, ½, ¼, ⅛...and so on). Some of the works Newton had already read used infinite series to attack a variety of questions—for one, chasing down ever more precise values for that bane of middle school geometers, π (the number used to calculate the circumference of circles). Newton, with his exceptional ability to speak both algebra and geometry, began to use infinite series to work out how curves behave. One of his favorite tricks was to think about the area under a curve—all that space on the graph between the curve and the x axis—and then build out a series that would add together smaller and smaller patches of that area until the sum of all those terms approached the entire territory and number being sought. Newton applied that idea to a wide range of different curves. He wrote out sequences. He plugged in numbers. He exhausted himself in calculation, cranking his exercises out to fifty decimal places and more.

He totaled his sums—and then discovered what modern mathematics calls the generalized binomial theorem. This result allowed Newton to solve a wide range of specific algebraic equations, including, most significantly, the problem of the area beneath a curve (called quadrature), not just for one shape at a time, but for whole classes of curves. It was a discovery that became one of the pillars of modern mathematics.

As he played with his series, he noticed that in some of them each step in the calculation added a smaller and smaller amount to the total. Extending the operation by hand—row after row of numbers, a strangely beautiful triangle, growing across the page—produced a better and better fit to the ultimate answer. The endpoint, well beyond the stamina of even so heroic a numbers-cruncher as Newton, was obvious: the last terms in such series must dwindle toward nothing. Toward, but never all the way there, an infinitely small approach to zero.



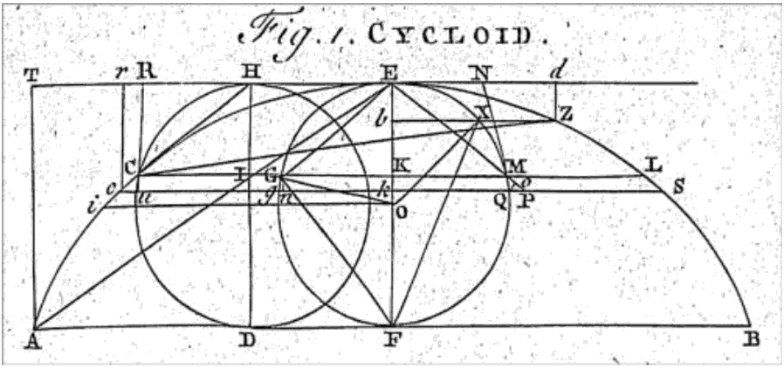
Newton's calculation of logarithms

Newton was not the first to ponder such infinitesimals. The Greek philosopher Zeno had played with the idea in his famous paradox: the race between the hero Achilles and a tortoise. With a fine sense of fair play, fleet-footed Achilles gave his opponent a head start. According to Zeno, that meant that no matter how much faster Achilles ran, he'd never overtake the tortoise. His reasoning was that in the time it took him to reach where the tortoise had just been, the reptile would move a little farther. When Achilles moved to that point, the tortoise would have moved again, and so on, forever. That increment of distance could get as small as you like, Zeno said, but it would never quite disappear. Hence, the tortoise would beat Achilles every time.

That's obviously absurd: in real life, an Achilles would charge past a tortoise, no matter how generous the head start. As early as Aristotle, logicians offered formal arguments to refute Zeno. But neither philosophical rigor nor common sense could erase the uneasiness produced by the idea of ever-smaller quantities. Many, like Descartes, simply didn't want to wrestle with an increment so tiny that it was effectively but not quite zero. Galileo knew that there was something vital about that infinitude but quailed before its mystery, "incomprehensible to our understanding." That is: there was, as yet, no established mathematical procedure that could use quantities indistinguishable from nothing to demonstrate that yes, in fact, Achilles smokes the tortoise every time. Newton himself, in his first months at Woolsthorpe, was often perplexed, straining to interpret the difference between almost zero and zero itself. But he didn't linger in the tangled metaphysics of a nothing that wasn't quite nothing. Instead, he put it to use.

In one case, Newton wanted to be able to identify how much a curve was curving at any point: how steep it might be, and how that steepness—Newton called it "the crookedness in lines"—changed at each point along the figure. Here, he used infinitesimals to produce a straight line whose slope could be calculated and that touched the curve at just that one point and no other—what's called a tangent.

Such problems took Newton unequivocally beyond classical approaches, in which the curves he was trying to understand had been examined as whole, finished phenomena, parabolas or ellipses or anything else of interest as the object of study. But Newton's thinking in the last months of 1665 employed his genuinely new way of seeing, in which the mathematical objects he analyzed emerged in the solutions to equations, point after point accumulating along the figure. He wasn't completely free of the older view as he pondered the tricks that schoolmasters used to construct the canonical curves without bothering with any algebra: a string attached to a peg that could be used to generate a circle; the same string fitted to two pegs to trace out an ellipse; and so on. He thought about more elaborate "mechanical" ways complex curves can emerge—the cycloid, for example, a form traced by a point on the rim of a wheel that rolls in a straight line—and others, still more complicated.



The making of a cycloid, from an eighteenth-century encyclopedia

In all those ways of ending up with a curving line on a page, there was one common theme: every curve was a map of motion, a mathematician's travelogue. A point travels through space, and its trail, its trace, creates the stuff of geometry. Crucially, sometime during these months, Newton realized that this approach, the "generation of figures by motion," could apply not just to abstract travel, the path of points in Cartesian spaces, but to the real stuff of the real world. In other words, motion in the universe, and not just in the mind's eye of the geometer, could be expressed in the mathematics he was inventing.

Newton did not grasp the full implication of this work all at once. He understood at least the mathematical side of his breakthrough by as early as November 13, 1665. In the paper he wrote then, he described the "infinitely little lines" that accumulated at each infinitely brief instant of time as his figures evolved. His breakthrough came when he realized that his two seemingly separate questions—how a curve bends and how much of the Cartesian plane it encloses—are actually twin faces of the same problem. Every change in the slope of a curve affects how much that shape encloses beneath it, and the same is true in reverse: the accumulation of territory under a curve reflects the shifting trace of that geometrical figure.

With that insight Newton arrived at a discovery that, on its own, would have made him one of the most famous thinkers who ever lived. Figuring out how to characterize how the shape of a curve is changing at any point in time is the core of what is now called differential calculus, which he then extended to integral calculus, which addresses the questions relating to the areas bounded by such curves. Taken together, those two interrelated ideas, as developed and extended, remain the foundational mathematics of material experience.

Newton never underestimated his own powers. He had to have grasped the importance of his accomplishment in those few months of enforced seclusion on his farm. Yet for most of the next two decades, he kept this new mathematical insight almost entirely to himself.

Still, this was the inflection point, after which the way humankind understood its circumstances would be irreversibly altered from what had been known before. What is motion but change over time? And what is the world but matter in motion, an ever-transforming flux, continuously transforming as the instants pass into seconds, hours, years?

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THE INVENTION OF the calculus, the mathematics of change, was one of the keys to what we now call the Newtonian revolution—and Newton in his miracle year put his breakthrough into almost immediate use. As 1666 began and the plague continued to rage, Newton turned from pure math to questions of material experience. At the heart of his inquiry lay the problem of gravity. As he told the story sixty years later, the essential clue to his ultimate theory came to him during the summer of 1666. One day he found himself in his garden "in a contemplative mood." The tree in front of him was heavy with fruit. Suddenly, an apple fell—an utterly ordinary occurrence. And yet, it nagged at him. "Why should that apple always descend perpendicularly to the ground?" he recalled asking himself. "Why should it not go sideways or upwards? but constantly to the earth's center?"

Why indeed? The myth of genius has asserted that this was all it took: in the not-quite-infinitesimal slice of time it took for the apple to drop to the ground, Newton grasped the ultimate prize, his theory of gravity. In the moment, so the story goes, he knew that matter attracts matter in proportion to the mass contained in each body divided by the square of the distance between them; that the tug is between the center of each mass; and—the ultimate prize—that the power "like that we here call gravity…extends its self thro' the universe."

This much is true: the tree itself was real. After his death, the original at Woolsthorpe was still known in the neighborhood as Sir Isaac's tree. Every effort was made to preserve it as long as possible, until it finally collapsed in a windstorm in 1816. It rerooted itself and can still be seen at Woolsthorpe, while grafts from the tree have been used to propagate clones of Newton's apples since the 1820s.

But even if Newton watched the apple fall (and thought about gravity as it plummeted) it still took him decades to work out his ultimate theory. He used his newly gained mastery of the mathematics of circular motion to discover why things—including us—don't simply fly off the surface of the earth, given the Copernican realization that the earth doesn't sit still at the center of the cosmos but rather travels at an impressive speed, spinning on its axis as it tracks around its central sun. He calculated the strength of the so-called centrifugal force that should be hurling us into space. He put together that number with a rough approximation for the earth's size—a number refined over the previous two centuries of European exploration by sea. Taken together, that was enough information to estimate the outward acceleration experienced at the surface of a revolving earth—how strongly any of us are being pushed out into space.

Then he performed the other half of the analysis, considering the downward tug at the surface of the earth of what he called gravity in something like the modern sense of the term. Galileo had already observed the acceleration of falling bodies, but Newton trusted no measurement so well as one he made himself, so he reworked that earlier result by studying the motion of a pendulum—an experiment that brought him close to the modern value for the earth's pull. He knew that his data were still imperfect, but, he wrote, he "found them answer pretty nearly"—by which he meant that he was able to calculate a result that made sense of the evident reality. The gravitational force holding our feet to the ground is (clearly) more than strong enough to do the job—in his calculation, approximately three hundred times stronger than any centrifugal urge to launch us upwards.

That result, at once imprecise and spectacular, would also have placed Newton in the vanguard of European natural philosophy if only anyone had heard about it. He was not yet fixed in his habit of silence, a determination reached a few years later, after a few bruising exchanges with other learned men. But isolated on his farm, he remained focused on the work at hand, applying his almost daily expanding mathematical skill to physical questions. Applying numbers to a concrete question—why stuff sticks to our planet's surface—transformed the pure mathematical reasoning within his calculus into a literally down-to-earth experience. Newton's work now became one of the early examples of what we would call a mathematical model, a representation of some aspect of nature abstracted into a form that could be manipulated, extended, and solved. Today we are utterly immersed in the Newtonian worldview, in which these models, systems of equations, are understood to be properties of the universe. During Newton's miracle year, there was no such recognition, not yet. His next move, though, would push him ever closer to the ultimate triumph, his demonstration that the book of nature is written in the language of mathematics.

The fall of the apple had produced a breakthrough, but not a fully realized theory of gravity itself. In a leap of imagination that is still astounding, Newton realized that whatever pulled that piece of fruit toward the ground must have been the same phenomenon that held the moon in its orbit—tracing a path around the earth as our planet's inward pull counteracted the moon's urge to shoot off into space. At some distance from the earth, those two impulses must balance. Sitting there, an object would fall forever, tracing a (nearly) circular path around the center of the earth. Our moon is held to its course by the same phenomenon, the earth's gravity, that drew Newton's apple to the ground.

The insight was there, but his first attempt to write down the mathematics of gravity wasn't quite right; he would arrive at his famous "universal law of gravitation" only in the mid-1680s. But the apple (if Newton's late-in-life tale is to be believed) did give him the critical piece of the puzzle: laws of nature are universal. Abstracting experience into equations, such laws penetrate beneath all the surface confusion of experience to reveal common patterns and deep truths that govern the cosmos. Most important, this new quantitative approach to nature offered the gift of prophecy: calculate now, and you can find where the moon or Jupiter or whatever will be, days, years, centuries from now. Though Newton called what he did in that Lincolnshire farmhouse "natural philosophy," this was science in its (early) modern form.

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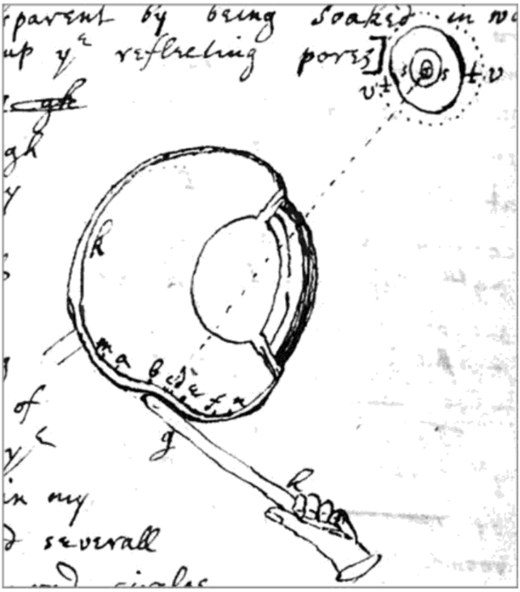
THERE WAS ONE more move Newton made to complete this new approach to nature. A system of equations could yield a portrait of some aspect of the wide world, but any such model still needed reliable knowledge extracted from the natural world to make the connection between math and experience. Observation, measurement, and especially a commitment to rigor were keys to Newton's new approach to natural philosophy: it was essential to test the world precisely and reliably enough so that any mathematical analysis of what was going on could yield a real insight into reality. One of the reasons Newton is remembered as perhaps the greatest genius in history is that from the beginning he did just that, plunging deeply not just into mathematics but into measurement of the world—at times to his own peril.



Newton’s drawing of his bodkin experiment

For example, in the early 1660s he wanted to know how the shape of the human eye might affect the perception of color. To find out, he turned to the nearest experimental subject, himself, and stuck a bodkin—a blunt needle—into the bottom of his eye socket and levered up. He meticulously recorded his results, including defining the curve he induced in his eyeball (“ye curvature a b c d e f”) and noting that the colored circles grew brighter “when I continued to rub my eye with ye point of ye bodkin.” His sketch of what he did to himself is at once meticulous and stomach roiling, a measure of both the urgency of his hunger for data and his utter recklessness.

Such mad hunger would seize Newton over and over again—he would later pursue his alchemical experiments so relentlessly that he drove himself to the point of physical exhaustion and, at least once, in 1693, tipped all the way over the edge into true mental collapse, months of silence and paranoid misery. But such excess shouldn’t obscure his deeper and lifelong commitment to a cooler empiricism: the need to base any scientific speculation on the solid ground of rigorous and systematic observation.

That's what occupied him in the last months of his plague exile: optical investigations that demanded hands-on effort in a series of organized, rigorous experiments with prisms and other apparatuses to tease apart the properties of color and light. The work ultimately produced what he called the *experimentum crucis*. That was his crucial demonstration—that sunlight, so-called white light, is actually a blend of distinct individual colors, the rainbow spectrum from red to blue.

The creation of new knowledge of the world required theories, ultimately mathematical accounts of the relationships between phenomena and events. It also needed a careful, logically coherent approach to the collection of data, observations and experiments that could probe the material world. As his miraculous year unfolded, Newton found himself tracing this arc: through each particular advance, from pure mathematics to what he was able to deduce as he twisted a triangular piece of glass, he uncovered not just previously unknown facts but a whole new way of organizing that knowledge into what he would later call, accurately, a "System of the World."

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BEYOND WOOLSTHORPE AND its scenes of revolutionary intellectual transformation—all completely unknown outside the farmhouse walls—the rest of Newton's world, haltingly, began to reassemble itself. By mid-March 1666 the city of Cambridge marked six weeks without a single plague death. The university reopened, and Newton returned to his rooms on or around March 20. Then, on Wednesday, June 6, Jane Ellingworth, a seamstress living on Penny Farthing Lane, felt poorly. Her father brought her a cup of ale and urged her to bed. She died the next day. The infection spread, with deaths reaching double digits in the city within two weeks. The colleges closed again, and Newton retreated to the countryside once more. The plague burned itself out over the summer, and by the end of the year Newton felt it safe enough to travel back to the university. He would remain there for the next thirty years.

By the time Newton resumed his almost-cloistered life in Trinity College, the onetime center of the epidemic had been utterly transformed. London's parish records reported a total of 68,596 plague deaths for 1665. The true figure was certainly higher. But the toll dropped during the winter, and stayed low, with only 2,000 more deaths from the disease tallied through all of 1666. Then, just as it appeared that the epidemic was truly done, came the four days in September when the Great Fire of London destroyed most of what lay within the old city walls, along with some newer neighborhoods to the west. Four hundred and thirty-six acres burned; at least thirteen thousand homes were destroyed. So were 87 out of the city's 109 churches, including old St. Paul's Cathedral. When that giant building caught fire, the tons of lead in its roof melted, creating a river of liquid metal flowing into the Thames.

A new London began to rise almost immediately. The fire seemed to obliterate the plague, though that could well have been a coincidence in timing rather than the result of any lasting impact on the city's rat population. Christopher Wren—often with the aid of his colleague in the nascent Royal Society, Robert Hooke—took the lead in restoring sacred London, building fifty-one parish churches along with his crowning monument: the new St. Paul's, with its glorious and technically sophisticated dome.

Life in the capital soon returned to an approximation of its preplague normal. The savants, Hooke and Wren among them, resumed weekly meetings at the Royal Society. Their conversations overflowed into the invisible university housed in the still-exotic coffeehouses and inns of the rebuilt city. Some of that talk was more enthusiastic than rigorous: at early meetings, the Society heard reports on "a Very Odd Monstrous Calf" and "Of the Way of Killing Rattle-Snakes," presented alongside "A Spot in one of the Belts of Jupiter" and "General Heads for a Natural History of a Country." Newton himself took no part in that eager, hungry, small "c" catholic pursuit of new knowledge. It would take him twenty years and more to organize the results of the plague years into a fully realized body of work. He did so mostly in silence. He had some contact with members of the nascent Royal Society in the early 1670s. But he soon disappeared from the view of learned Europe. That was partly because he resented challenges to his results, partly because of his determination never to share a discovery before he was certain, and partly because for many of those "missing" years he pursued lines of inquiry that he actively wanted to keep secret: inquiry into heterodox religious beliefs and into the ancient pursuit of alchemy, which he saw as one more way to investigate change in nature. He wrote of his alchemical experiments to a handful of fellow searchers, but he rarely communicated in any public way with his fellow natural philosophers in London, and he visited the capital even less.

But such silence did not mean that he was unmoved by the same impulses driving the early Royal Society men, with their public commitment to knowledge for its own sake—and to the application of whatever could be discovered to practical uses. From the beginning, he too recognized that natural philosophy could comprehend daily life as well as the broad sweep of nature. As early as 1664, for example, before he plunged into the question of gravitation, he laid out a geometrical approach for calculating compound interest—his first contribution to the mathematics of money. A decade later, he turned his quantitative virtuosity to the service of his home institution, helping Trinity College's bursar analyze how much rent he should charge for land—farms that the college owned. Newton could count and Newton could think, and his work here—pricing an asset that offered payments over time—already hinted at the possibility that those two skills could make a man rich.

If that thought crossed his mind in his Cambridge years, he didn't act on it. His full immersion into the world of money—on his own account as well as in service to the crown—would come a full three decades after his miracle year, when he took up new duties as an officer of the Royal Mint. Others, though, were beginning to recognize that there might be a connection between quantitative reasoning and wealth. They would pursue solid, empirical starting point, so as "to consider only such Causes," in his words, "as have visible Foundations in Nature."

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THAT WAS THE grand vision of his later years. Little in Petty's origins suggested he would rise to such grand ambition. He was born on May 26, 1623, in the town of Romsey, to a father who was an unsuccessful clothier and dyer. He left his local school at thirteen, already the master of "a competent smattering of Latin, and…entered into the Greek." Before his fifteenth birthday he made his escape from Romsey and its meager possibilities, signing on with a merchant ship working the cross-Channel trade with France. Here, fortunate ill-fortune intervened. No natural sailor, he broke his leg aboard and was turned ashore at the Norman port city of Caen. The Jesuits of the University of Caen took him in and exposed him to some of the new, humanistic learning then spreading across Europe.

Petty left Caen in the late 1630s, still in his teens, and returned to England, already showing the magpie-like mental agility of the polymath he was becoming. Before his twenty-first birthday he managed to write up astronomical ideas, publish poetry, complete "Severall paintings and drawings," and perform some jobs for the navy. He paused to train as a physician—a curriculum that exposed him to yet more new ideas, about mechanical cause and effect, anatomy, and chemistry. When he was done, he was both a doctor and an example of a new kind of man, a "virtuoso," as the growing network of London's eager investigators styled themselves. He and they were committed to what was already being called natural philosophy, with its program of discovery through experiment, observation, and the unequivocal testimony of nature. There was only one problem. He was still poor. His wit kept him fed and clothed, but he wanted more.

His fortunes would change when he became a winner in one of the most vicious episodes in two brutal decades of misery on the wretched island of Ireland. The Irish Rising of 1641 had been a violent mess that led to the creation of the Irish

Catholic–dominated Confederation, a short-lived, contested, but more or less autonomous government with at least nominal authority over much of the island. The Confederation existed in a state of near-continuous conflict with English royalists in Ireland and Protestant power centers aligned with the parliamentary side of the ongoing English Civil War. Ultimately, when King Charles I offered official toleration of Catholic worship in Ireland, along with other provisions that amounted to recognizing Irish autonomy, the Confederation agreed to place its armed forces under English officers. The deal didn't hold. Charles tried and failed more than once to import Irish soldiers to aid him against Oliver Cromwell's New Model Army, Parliament's military force. With the king's final defeat and execution on January 30, 1649, the victors saw in the Confederation a rebellious province that had, more or less, lined up with the losers. Ireland to the new English Commonwealth was both threat and prize.

Cromwell invaded seven months after the king's death, landing at Dublin on August 15, 1649. It was a bloody, brutal campaign. After his first major victory, the capture of Drogheda, two thousand Irish Royalist soldiers were executed, an atrocity followed by a general massacre of both combatants and civilians at Wexford. By the spring of 1650, the invaders had managed to retake most of Confederate Ireland, and Cromwell himself returned to London. There was just one problem: he left behind an army that hadn't been paid, as almost a decade of civil war had left Parliament as much as £3 million in the hole.

The new government couldn't rely on the usual habits of overstretched monarchs and simply borrow the money. In the turmoil and uncertainty after Charles's beheading, traditional lenders had become skittish. That forced the English back to another old trick, the brigand's solution: trade the chance of loot to come for cash in hand. It worked. The soldiers who did the actual fighting went without pay, and the same went for the army's suppliers—to whom were added the so-called adventurers, those bold souls who were willing to lend money to the new English government. In return they received the promise of…Ireland, almost all of it, to be taken from Catholic landowners along with anyone else who had chosen the wrong side during the Civil War.

After the victory, though, there was an obstacle between the English and their spoils: figuring out what Ireland was actually worth, piece by piece. By 1653, with the countryside at last pacified, the need to do so became acute. A first attempt to catalog the property to be forfeited was merely a summary accounting of the total amount of available land. The second was primarily a document review, existing records of boundaries and the rents and other measures of value of each plot of land. This "Civil Survey" was widely believed to be inaccurate at best, and, by the end of 1654, thousands of trained men with guns remained without their promised reward. Almost two years into the process, they were becoming just a bit impatient.

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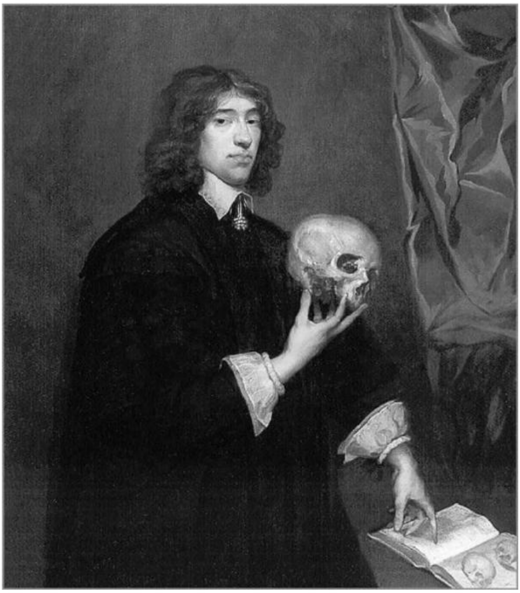
ENTER WILLIAM PETTY. He had wangled the post of physician-general to the army in Ireland, and moved to Dublin in 1652. Initially, he alternated practicing medicine with more of the natural philosophizing he'd enjoyed in London, anatomizing local fauna with the Anglo-Irish aristocrat Robert Boyle, for example, or diving into studies of the Irish harp. But as the early surveys faltered, Petty saw his chance. In what amounted to an intellectual coup, he pitched the army leadership a new approach to the mapping problem. The incumbent surveyor-general had opted to measure only land marked for confiscation. In place of the "absurd and insignificant way of surveying" of the Civil Survey, with its primary focus on land ownership records and not on a direct account of the assets to be seized—improvements to the property, livestock, tools and the like—Petty offered to measure everything: the whole of Ireland, its ownership, its geography, all of its "rivers, mountains, ridges, rocks, sloughs and bogs," along with the houses, barns, fences, and all the rest that made up the island's real property. And he would do all this for a fee to be paid mostly in thousands of acres of Irish land.



William Petty in 1651

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THE AUTHORITIES ACCEPTED Petty's proposal in December 1654. He began immediately, swiftly surpassing (as he'd promised) the incomplete and disputed work of his predecessors. He committed to direct empirical observation. He sent to London for new surveying tools, to be produced by modern methods—"The said Petty, consideringe the vastnesse of the worke, thought of dividinge both the art of makinge instruments, as also using them into many parts." That is: he set it up so that one craftsman would make measuring chains, another compass needles; woodworkers would concentrate on building cases; and so on. This isn't quite Adam Smith on the manufacture of pins, but Petty's idea is recognizably kin to that vision of rationalizing human behavior to some greater (and more interchangeable) end. Armed with these standardized kits, teams of surveyors and assistants set out, guarded by soldiers, and working with designated "bounders"—men who could confirm local property lines set out across Ireland.

Down Survey capped a decade-long demographic catastrophe that killed as many as one of every three Irish men, women, and children.

There's no evidence that Petty himself delighted in such immiseration. He would later calculate that half a million Irish men, women, and children had lost their lives as a direct or indirect result of the years of war, "for whose Blood some body should answer both to God and the King." But he accepted no reproach for his part in separating the survivors from their property. He had been asked to solve a technical problem: measure England's newly reconquered prize. What was to be done with his report was a political decision (albeit one from which Petty himself profited). The lesson Petty drew from his Irish experience was that applying formal rigor to observation and measurement—the same concept his London circle of virtuosos had begun to explore—actually worked in the real world.

Most important was the rigor with which Petty created the tools of data collection for his survey, standardizing them to complete one of the first modern works of political geography. This was the new natural philosophy brought (literally) down to earth, Ireland anatomized on paper. The final result rendered all the prolific variety of a landscape into a form—maps—that could be read by anyone. Most important, the Down Survey caught the same kind of insight Newton would later capture to transform natural science. It combined observation with numbers. In this, Petty's first great project, it was still a very simple relationship, just assessments of land that could be expressed as the pounds, shillings, and pence owed to each creditor. Soon, though, Petty would come up with a much more ambitious vision, one that imagined politics itself, the art of statecraft, as a form of mathematical argument.

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PETTY HAD COME to Dublin a poor, clever, cocky twenty-nine-year-old. Seven years later he returned home a rich man—master of the thousands of acres of Irish land that formed his meant proposing a change to who lived in Ireland as a way to make the territory more productive and its people less restive. He wrote, “If an exchange was made of but about 200,000 *Irish* and the like number of *English* brought over in their rooms, then the natural strength of the *British* would be equal to that of the *Irish,*” which would mean, Petty added, that “the *Irish* would never stir upon a National or Religious Account,” while the like number of Irish who were shifted across the Irish Sea would be far outnumbered by the English at home.

Petty went on to suggest a refinement to that initial plan of forced relocation. Among the displaced, he said, there should be twenty thousand marriageable Irish women to be distributed among England’s parishes each year. To keep gender ratios stable (and with them, the number of marriageable couples), the same number of English women should be sent to Ireland. These would marry locals—and here we come to the point of Petty’s exercise in social engineering—and thus civilize Irish bachelors, creating Anglo-Irish households conforming to English culture, domestic behavior, and allegiance.

Petty didn’t stop with the simple manipulation of populations. He argued that the government should gather statistics to enable the leaders of a mostly agricultural economy to manage their affairs. “To make nearer approaches to the perfection of this Work,” he wrote, “ ’twould be expedient to know the Content of Acres of every Parish, and withal, what quantity of Butter, Cheese, Corn, and Wool, was raised out of it for three years consequence”—to count in each plot of land how much could be produced by how many workers. Repeat the exercise over the entire realm, and the result would be a whole new insight into the wealth of the nation: a level of quantitative detail that would enable the arithmetician “to make a *Par* and *Equation* between Lands and Labour.” Petty’s approach wouldn’t offer what we would recognize as a measure of gross domestic product in anything like a modern calculation, but it is recognizably an ancestor to such national accounting. This was a modern idea, born of the conviction Petty shared with his Royal Society peers: everything was or could be made to be expressed mathematically, thus revealing relationships between everything that empirical experience could count, weigh, or measure.

Fifteen years later, Isaac Newton would publish his great account of celestial motion. It's easy to exaggerate the connection with Petty's attempt to quantify economics and politics, certainly—but the resonance between them is no mere coincidence either. Newton and his colleagues advanced mathematical models of motion to the point where they could test them against nature—and generate useful, accurate, *true* predictions. Petty never approached that kind of accuracy, nor were there a handful of axioms about human experience that could support an account of the human cosmos analogous to the compact set of physical laws Newton would use to build his universe. Still, he argued that even simple quantitative connections—acres to butter—exposed authentic patterns of human experience.

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PETTY WOULD TURN his political arithmetic to other challenges over the next fifteen years: weighing the relative wealth and power of England, France, and the Dutch through various statistical measures, for example, and attempting to calculate the prospects of the young English colonies in North America. Near the end of his life, he came up with a last, terrifying proposal for Ireland. He would cut the island's population down to a tiny fraction, leaving just a handful behind to act as drovers on what would become a giant cattle ranch. Everyone else would be pressed into the service of another attempt to engineer nations via demographics: almost all the Catholics in Ireland would be brought to England in support of King James II's doomed hope of re-Catholicizing his realm. (Petty wasn't the only Englishman to prosper through the tumult of England's bloody seventeenth-century politics, but it's a mark of his flexibility that he was able to serve both Cromwell's ends at the beginning of his career and James's passions at its end.)

Nothing came of these later Irish schemes, either Petty's dream of taming unruly papists in their homes or his terrifying