Five Equations That Changed the World

The Power and Poetry of Mathematics

Michael Guillen, Ph.D.

HYPERION

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Introduction

Mathematical Poetry

Poetry is simply the most beautiful, impressive, and widely effective mode of saying things.

MATTHEW ARNOLD

Mathematics is a language whose importance I can best explain by starting with a familiar story from the Bible. There was a time, according to the Old Testament, when all the people of the earth spoke in a single tongue. This unified them and facilitated cooperation to such a degree that they undertook a collective project to do the seemingly impossible: They would build a tower in the city of Babel that was so high, they could simply climb their way into heaven.

It was an unpardonable act of hubris, and God was quick to visit his wrath on the blithe sinners. He spared their lives, but not their language: As described in Genesis 11:7, in order to scuttle the blasphemers' enterprise, all God needed to do was "confound their language, that they may not understand one another's speech."

Thousands of years later, we are still babbling. According to linguists, there are about 1,500 different languages spoken in the world today. And while no one would suggest that this multiplicity of tongues is the only reason for there being so little unity in the world, it certainly interferes with there being more cooperation.

Nothing reminds us of that inconvenient reality more so than the United Nations. Back in the early 1940s, when it was first being organized, officials proposed that all diplomats be required to speak a single language, a restriction that would both facilitate negotiations and symbolize global harmony. But member nations objected—each loath to surrender its linguistic identity—so a compromise was struck; United Nations ambassadors are now allowed to speak any one of *five* languages: Mandarin Chinese, English, Russian, Spanish, or French.

Over the years, there have been no fewer than 300 attempts to invent and promulgate a global language, the most famous being made in 1887 by the Polish oculist L. L. Zamenhof. The artificial language he created is called Esperanto, and today it is spoken by more than 100,000 people in twenty-two countries.

However, as measured by the millions of those who speak it fluently and by the historic consequences of their unified efforts, *mathematics* is arguably the most successful global language ever spoken. Though it has not enabled us to build a Tower of Babel, it has made possible achievements that once seemed no less impossible: electricity, airplanes, the nuclear bomb, landing a man on the moon, and understanding the nature of life and death. The discovery of the equations that led ultimately to these earthshaking accomplishments are the subject of this book.

In the language of mathematics, equations are like poetry: They state truths with a unique precision, convey volumes of information in rather brief terms, and often are difficult for the uninitiated to comprehend. And just as conventional poetry helps us to see deep *within* ourselves, mathematical poetry helps us to see far *beyond* ourselves—if not all the way up to heaven, then at least out to the brink of the visible universe.

In attempting to distinguish between prose and poetry, Robert Frost once suggested that a poem, by definition, is a pithy form of expression that can never be accurately translated. The same can be said about mathematics: It is impossible to understand the true meaning of an equation, or to appreciate its beauty, unless it is read in the delightfully quirky language in which it was penned. That is precisely why I have written this book.

This is not so much an offspring of my last book, *Bridges to Infinity: The Human Side of Mathematics,* as it is its evolutionary descendant. I wrote *Bridges* with the intention of giving readers a sense of how mathematicians think and what they think about. I also attempted to describe the language—the numbers, symbols, and logic—that mathematicians use to express themselves. And I did it all without subjecting the reader to a single equation.

It was like sweet-tasting medicine offered to all those who are afflicted with math anxiety, individuals who normally would not have the courage or the curiosity to buy a book on a subject that has consistently frightened them away. In short, *Bridges to Infinity* was a dose of mathematical literacy designed to go down easily.

Now, emboldened by having written a successful book that contains no equations, I have dared to go that one step further. In this book I describe the mathematical origins of certain landmark achievements, equations whose aftereffects have permanently altered our everyday lives.

One might say I am offering the public a stronger dose of numeracy, an opportunity to become comfortably acquainted with five remarkable formulas in their original, undisguised forms. Readers will be able to comprehend *for themselves* the meaning of the equations, and not just settle for an inevitably imperfect nonmathematical translation of them.

Readers of this book also will discover the way in which each equation was derived. Why is that so important? Because, to paraphrase Robert Louis Stevenson: When traveling to some exotic destination, getting there is half the fun.

I hope that the innumerate browser will not be scared off by the zealousness of my effort. Rest assured, though these five equations look abstract, most certainly their *consequences* are not—and neither are the people associated with them: a sickly, love-starved loner; an emotionally abused prodigy from a dysfunctional family; a religious, poverty-stricken illiterate; a soft-spoken widower living in perilous times; and a smart-alecky, high school dropout.

Each story is told in five parts. The Prologue recounts some dramatic incident in the main character’s life that helps set the tone for what is to follow. Then come three acts, which I refer to as Veni, Vidi, Vici. These are Latin words for “I came, I saw, I conquered,” a statement Caesar reportedly made after vanquishing the Asian king Pharnaces. Veni is where I explain how the main character—the scientist—comes to his mysterious subject; Vidi explains historically how that subject came to appear so enigmatic; Vici explains how the scientist manages to conquer the mystery, resulting in a historic equation. Finally, the Epilogue describes how that equation goes on to reshape our lives forever.

In preparing to write this book, I selected five equations from among dozens of serious contenders, solely for the degree to which they ultimately changed our world. Now, however, I see that the stories attached to them combine fortuitously to give the reader a rather seamless chronicle of science and society from the seventeenth century to the present.

As it turns out, that is a crucial period in history. Scientifically, it ranges from the beginning of the so-called Scientific Revolution, through the Ages of Reason, Enlightenment, Ideology, and Analysis, during which science demystified each one of the five ancient elements: Earth, Water, Fire, Air, and Ether.

In that critical period of time, furthermore, we see: God being forever banished from science, science replacing astrology as our principal way of predicting the future, science becoming a paying profession, and science grappling with the ultra-mysterious issues of life and death and of space and time.

In these five stories, from the time when an introspective young Isaac Newton sits serenely beneath a fruit tree to when an inquisitive young Albert Einstein nearly kills himself scaling the Swiss Alps, we see science wending its way from the famous apple to the infamous A-bomb. Which is to say, we see science going from being a source of light and hope to its also becoming a source of darkness and dread.

Writers before me have chronicled the lives of some of these five scientists—all too often in frightfully long biographies. And writers before me have reconstructed the pedigree of some of these intellectual innovations back to the beginning of recorded history. But they have never focused their roving attentions on the small number of mathematical equations that have influenced our existence in such profound and intimate ways.

The exception is Albert Einstein's famous energy equation $E = m \times c^2$, which many people already know is somehow responsible for the nuclear bomb. But for all its notoriety, even this nefarious little equation remains in the minds of most people scarcely more than a mysterious icon, as familiar yet inexplicable as Procter & Gamble's corporate logo.

What exactly do the letters E, m, and c stand for? Why is the c squared? And what does it mean for the E to be equated with the $m \times c^2$? The reader will learn the surprising answers in "Curiosity Killed the Lights."

The other chapters deal with scientists less well known than Einstein but who are no less important to the history of our civilization. "Between a Rock and a Hard Life," for example, concerns the Swiss physicist Daniel Bernoulli and his hydrodynamic equation $P + \rho \times ½ v^2 = \text{CONSTANT}$, which led ultimately to the modern airplane. "Class Act" is about the British chemist Michael Faraday and his electromagnetic equation $\nabla \times E = -\partial B/\partial t$, which ultimately led to electricity.

"Apples and Oranges" tells the story of the British natural philosopher Isaac Newton and his gravitational equation $F = G \times M \times m \div d^2$—which led not to any specific invention but to an epic event: landing a man on the moon.

Finally, "An Unprofitable Experience" is about the German mathematical physicist Rudolf Julius Emmanuel Clausius and his thermodynamic equation (or more accurately, his thermodynamic *inequality*) $\Delta S_{\text{universe}} > 0$. It led neither to a historic invention or event but to a startling realization: Contrary to popular belief, being alive is unnatural; in fact, all life exists in defiance of, not in conformity with, the most fundamental law of the universe.

In my last book, *Bridges to Infinity*, I suggested that the human imagination was actually a sixth sense used to comprehend truths that have always existed. Like stars in the firmament, these verities are out there somewhere just waiting for our extrasensory imagination to spot them. Furthermore, I proposed that the *mathematical* imagination was especially prescient at discerning these incorporeal truths, and I cited numerous examples as evidence.

In this book, too, readers will see dramatic corroboration for the theory that mathematics is an exceptionally super-sensitive seeing-eye dog. Otherwise, how can we begin to account for the unerring prowess and tenacity with which these five mathematicians are able to pick up the scent, as it were, and zero in on their respective equations?

While the equations represent the discernment of eternal and universal truths, however, the manner in which they are written is strictly, provincially human. That is what makes them so much like poems, wonderfully artful attempts to make infinite realities comprehensible to finite beings.

The scientists in this book, therefore, are not merely intellectual explorers; they are extraordinary artists who have mastered the extensive vocabulary and complex grammar of the mathematical language. They are the Whitmans, Shakespeares, and Shelleys of the quantitative world. And their legacy is five of the greatest poems ever inspired by the human imagination.

$$F = G \times M \times m \div d^2$$

Apples and Oranges

Isaac Newton and the Universal Law of Gravity

I sometimes wish that God
were back
In this dark world and wide;
For though some virtues he might
lack,
He had his pleasant side.

—GAMALIEL BRADFORD

For the last several months, thirteen-year-old Isaac Newton had been watching with curiosity while workmen built a windmill just outside the town of Grantham. The construction project was very exciting, because although they had been invented centuries ago, windmills were still a novelty in this rural part of England.

Each day after school, young Newton would run to the river and seat himself, documenting in extraordinary detail the shape, location, and function of every single piece of that windmill. He then would rush to his room at Mr. Clarke's house to construct miniature replicas of the parts he had just watched being assembled.

As Grantham's huge, multiarmed contraption had taken shape, therefore, so had Newton's wonderfully precise imitation of it. All that remained now was for the curious young man to come up with something, or someone, to play the role of miller.

Last night an idea had come to him that he considered brilliant: His pet mouse would be perfect for the part. But how would he train it to do the job, to engage and disengage the miniature mill wheel on command? That was what he had to puzzle out this morning on his way to school.

As he walked along slowly, his brain raced toward a solution. Suddenly, however, he felt a sharp pain in his gut; his thoughts came to a screeching halt. As his mind's eye refocused, young Newton came out of his daydream and beheld his worst nightmare: Arthur Storer, the sneering, taunting school bully, had just kicked him in the stomach.

Storer, one of Mr. Clarke's stepsons, loved to pick on Newton, teasing him mercilessly for his unusual behavior and for fraternizing with Storer's sister, Katherine. Newton was a quiet and self-absorbed youngster, generally preferring the company of his thoughts to that of people. But whenever he did socialize, it was with girls; they were tickled by the doll furniture and other toys he made for them using his customized kit of miniature saws, hatchets, and hammers.

While it was common for Storer to call Newton a sissy, on this particular morning, he was insulting him for being so *stupid*. Unfortunately, it was true that Newton was the next-to-lowest ranking student in the whole of Grantham's Free Grammar School of King Edward VI, seeded well below Storer. But the idea of this big bully thinking of himself as intellectually superior made the reclusive young man's thoughts turn from windmills to revenge.

As he sat at the back of the class, Newton usually found it easy to ignore what his teacher, Mr. Stokes, was saying. This time, however, he listened with interest. The universe was divided into two realms, each obeying a different set of scientific laws, Stokes instructed. The imperfect, earthly region behaved one way, and the perfect, heavenly region behaved another; both domains, he added, had been successfully studied and their respective ordinances deduced long, long ago by the Greek philosopher Aristotle.

For young Newton, suffering at the hands of an earthly imperfection such as Storer was proof enough of what Mr. Stokes was talking about. Newton hated Storer and his classmates for not liking him. Above all, he hated himself for being so unlikable that even his own mother had abandoned him.

God was the only friend he had, the pious young man thought, and the only friend he needed. Newton was a much smaller person than Storer, but with God's help, he certainly would be able to vanquish the offensive tormentor.

No sooner had Mr. Stokes dismissed class that day than Newton was out the door, waiting in the nearby churchyard for the bully. Within minutes, a boisterous crowd of students gathered round. Stokes's son selected himself referee, slapping Newton on the back as if to encourage him, while winking at Storer as if to say this was going to be as entertaining as watching Daniel being fed to the lions.

At first, no one cheered for young Newton. Instead, each time Storer landed a punch, the rowdy students whooped it up, egging on the ruffian to hit even harder the next time. When it seemed as if Newton had been beaten into submission, Storer straightened up and relaxed, grinning boastfully at his young peers.

As he turned to walk away, however, Newton struggled to his feet: He was not about to let Storer win the right to lord over him for the rest of his life. Alerted by shouts of warning, Storer wheeled around and was greeted with a kick to his stomach and a punch to the nose; Newton had drawn blood, and that reinvigorated him.

For the next several minutes, the two traded blows and wrestled one another to the ground. Time and again, Storer staggered away, thinking he had defeated Newton, only to be confronted anew.

When it was all over, the crowd was stunned into silence. As the young referee stepped in to congratulate the bloodied and exhausted Newton, however, the dumbstruck students stirred and began to cheer: Daniel had become David, they declared jubilantly, as they danced around the fallen Goliath.

Newton was more than satisfied with what he had done, but his schoolmates were not. As he attempted to walk away, young Stokes grabbed his shoulder and encouraged him to humiliate Storer. Newton hesitated, but wishing to gain the approval of his fellow students, he dragged the bewildered bully by the ears and slammed his face into the church wall. The crowd of young spectators squealed with delight as they swarmed around the dazed victor, patting him on the back and accompanying him all the way home with unrestrained shouts of celebration.

Having defeated Storer, Newton's attention quickly returned to the problem of training his pet mouse. Unfortunately for Newton, though, this meant returning to the behavior that had incited his tormentor in the first place.

In a matter of weeks, the still-bruised and -battered Storer worked up enough courage to begin reprising some of his old gibes. Worst of all, Storer's accusations still hit home: Despite his pugilistic victory, Newton remained the dunce of his class.

All his life, with God's help, young Newton had been able to withstand the hazing from insensitive oafs like Storer. But now that he had known the pleasure of being accepted by his compeers, of being loved, he found Storer's effrontery unbearable.

This time, he would truly finish the job he had only started in the churchyard.

In the months ahead, Newton paid attention in class as never before and studied his lessons at home. He submitted his completed homework on time and answered all of Mr. Stokes's schoolroom queries.

Gradually, miraculously, one desk at a time, young Newton earned his way to the head of the class. Literally now, he smirked inwardly, he could turn his back on everyone who had ever hurt his feelings or dared suggest they were better or smarter than he.

In the decades ahead, the scope of Newton's interests would expand from windmills to the universe as a whole. But one thing about him would never change: He would meet other antagonists—or people whom he perceived as antagonists—and each time, his obsessive desire for revenge and approval would impel him to an unprecedented understanding of the natural world.

Above all would be his unprecedented understanding of gravity, the force that had always kept our feet on the ground. Newton's stunning disclosure would *sweep* us off our feet, and in the end, our cherished notions about God and Heaven would come toppling down, just like the bully Storer.

VENI

Hanna Ayscough Newton was beside herself with anxiety. Her husband, Isaac, had left suddenly to rally round King Charles I, who had been driven out of London by riotous mobs and an angry, power-hungry Parliament. The king had sought refuge in Nottingham, only thirty miles away from the Newtons' hometown of Woolsthorpe, and from there had just declared war.

England had been involved in many hostilities, but none like this one. This was a declaration of civil war, pitting family members against one another. Ostensibly the conflict was over who would govern England—the royal sovereign or Parliament—but more fundamentally, it was a showdown between heaven and earth.

For centuries, monarchs the world over had been anointed by their country's highest-ranking religious figure; in England, it was the Archbishop of Canterbury. This was no mere ceremony; it was an acknowledgment that kings and queens were selected for office by God himself.

In politics, as in science, therefore, much of the seventeenth-century world consisted of two dramatically separate realms. Mere mortals inhabited the *earthly* realm, but kings and queens were above it all; they dwelt in some lofty, *heavenly* domain, exempt from obeying the strict rules and regulations they imposed on their subjects—and their parliaments.

Over the years, these heavenly appointed rulers had tussled with their earthly appointed parliaments about the details of day-to-day political power. In this regard, Charles had been no different; but now in the fall of 1642, for the first time ever, the two realms had gone to war over the issue of who was preeminent.

Parliament was demanding that Charles relinquish his control over church and state, faulting him for having levied taxes illegally and for having been so religiously intolerant that Pilgrims were now fleeing en masse to uncivilized colonies in America. "The question in dispute between the King's party and us," the rebellious Parliamentarians declared, "was whether the King should govern as a god by his will … or whether the people should be governed by laws made by themselves."

In response to this mutinous uprising, Charles had fled from his castle; in

Nottingham, he had organized an army of loyalists and was now advancing toward London. Though he and his army were well equipped and fired up, however, their first major battle against the parliamentary forces ended in a draw and left 5,000 soldiers dead.

Among them was thirty-six-year-old Isaac Newton, a yeoman farmer whose father had prospered under the king's controversial yet largely peaceful reign. It had been only last year that Newton had inherited his father's sizable manor—the largest in Woolsthorpe—and only this spring that he had married Hanna and conceived their first child.

Hanna was six months' pregnant when she received the devastating news. She understood and respected the importance of the king's war with Parliament, but she was alternately angry and grief-stricken that her husband had gotten himself killed and orphaned their child-to-be.

The only thing that consoled her was the common belief among villagers that posthumous children invariably grew up having special curative powers and particularly good fortune. She was even more heartened when she gave birth on December 25; a posthumous child born on Christmas Day, the villagers exclaimed, was destined most certainly to be someone very, very special.

No sooner had she laid eyes on the newborn, whom she named Isaac, however, than Hanna began to worry that the locals' joyous predictions would prove to have been premature. Her baby had been born several weeks too early; he was no bigger than a quart jar and gave every indication that he would not survive.

As the pessimistic news spread, the good folks of Woolsthorpe began to speak in hushed tones of a good omen gone bad. Two women sent on an errand on behalf of the newborn, in fact, did not bother to walk very quickly and rested many times along the way, so certain were they that the ill-fated child would die before they returned.

They were wrong. As the days passed, baby Isaac clung to life with increasing strength, revealing a stubbornness, a willpower so extraordinary the villagers appeared to have been vindicated after all: This son of a dead man, born on Christ's birthday, they whispered, was no ordinary human being.

During the first few years of his life, young Isaac Newton was so feeble he had to wear a neck brace to hold his head in place. Nevertheless, the danger to his life had passed, and everyone in Woolsthorpe assumed that mother and child would settle into a
l comfortable existence.

vere wrong. When Newton was only two years old, his mother
of marriage from the Reverend Barnabas Smith, a wealthy, sixty-
er from North Witham, a town located about a mile away. After
er, the Reverend William Ayscough, Hanna decided to accept,
whereupon she moved to North Witham *without* her son, whom she left in the care of her mother.

Being abandoned at such a young age would have been traumatic enough under normal circumstances. But this was 1645, and England's civil war was now raging throughout the countryside. Woolsthorpe, at first under the protection of the king, had been captured by Parliament. Every week, there was gunfire from mortal skirmishes being fought in the area and intrusions from raiding parties in search of provisions and billeting. All this chaos frightened the frail young Newton, and worse, when he cried for his mother, she wasn't there to comfort him.

Newton's grandmother tried her best to mollify him, but she herself was quite frightened by what was happening. Nearly all the able-bodied men of Woolsthorpe had been killed or called away to fight, leaving only clergymen to help defend the women and children against the bestialities of the warring armies.

Adding to his fright, in 1649, the youngster began to attend school. Being delicate by birth, he was afraid (and not welcome) to participate in the aggressive games played by the other boys. Being an orphan, moreover, he felt inferior to the other children, most of whom lived in homes enriched by the love of a mother and father.

He was even more discomfited later that same year when the village received news that the Puritan-dominated Parliament, led by Oliver Cromwell, had defeated the royal armies; King Charles himself had been beheaded. Over the years, young Newton had formed a vicarious attachment to the swashbuckling monarch, fully expecting that one day this surrogate father figure would come galloping in to rescue him and his village from the nasty Parliamentarians.

It was during these perilous years that young Newton came to cherish the companionship of his uncle, Hanna's brother, who lived two miles away. Like all Anglicans at the time, the Reverend Ayscough saw the civil war in religious terms, pitting the king—England's "Defender of the Faith"—against a Parliament controlled by Puritans.

Both sides were devoted Christians, of course, but they were split as to the way in which organized religion should be governed. Anglicans were administered by a hierarchy of clergymen, headed by the Archbishop of Canterbury, the English equivalent of the Pope. The Puritans were organized in a less hierarchical, more purely democratic, fashion. In truth, their differences were rather esoteric, yet mutual intolerance was causing them to kill one another.

Newton was far too young to understand any of this, but as he watched his uncle studying peacefully in the library, listened to his uncle speaking gently to his parishioners, young Newton became conditioned to associate a religious and scholarly lifestyle with safety and security.

In a short time, therefore, young Newton acquired the habit of turning away from the encircling chaos and toward his own thoughts. He sought out secluded areas, where he would sit for hours at a time, not so much to observe the natural world as to *immerse* himself in it.

The young man discovered that if he meditated single-mindedly on the minutiae of his surroundings, he was able to escape from his miserable existence and discover interesting things about Nature. For example, he noticed, rainbows always came in the same colors, Venus always moved faster than Jupiter across the night sky, and children playing ring-a-ring o'roses invariably leaned a bit backward, as if they were being nudged by some invisible force.

In these wholly encompassing immersions, the youngster was able to enter a sanctuary every bit as comforting as his uncle's rectory, without having to travel the two miles to get there. Best of all, he discovered true happiness for the first time in his life.

In 1649, Newton's newfound rapture was spoiled by the return of his mother and several young strangers. The Reverend Barnabas had died, but only after having fathered three small children, one of them less than a year old. Even now, even with his mother's return, young Newton fumed and fussed, he would not have her undivided love and attention.

During the first several months of her homecoming, Mrs. Newton-Smith tried to explain to her angry son that she had married the old rector solely to secure their long-term financial security. The rector of North Witham, she revealed, had paid for a renovation and expansion of the Newton's manor and bequeathed to young Newton a large parcel of land.

Nothing his mother said, however, could sweeten his bitterness at having been abandoned. Newton hated his mother and often had dreamed of setting fire to her and her second husband while they lay sleeping together.

For the next few years, therefore, though one civil war between king and Parliament had ceased, another raged between mother and son. Ultimately, the only thing that stopped it was forcible separation: This time, however, it was young Newton who left his mother.

It had come time for the twelve-year-old to attend grammar school in the city of Grantham, seven miles away. Since that was too far to walk, his mother had arranged for him to room and board with the Clarke family, longtime friends of the Newtons.

Having lived with a mother he hardly knew and three half siblings he didn't care to know, young Newton was unfazed by the idea of moving in with complete strangers; at least, he thought, they gave the appearance of being an honest-to-goodness family. There was Mr. Clarke, who ran his own apothecary; Mrs. Storer-Clarke and her four children from a previous marriage; they included a pugnacious son named Arthur and an attractive daughter, Katherine, who took an instant liking to the new boarder.

The Clarkes frequently entertained learned guests, so Newton's mind was kept well fed with food for thought. Most wonderful of all was Mr. Clarke's vast collection of books in the attic. Here was the perfect getaway, the ideal sanctuary, Newton enthused, as he proceeded to immerse himself in subjects ranging over the entire intellectual spectrum.

The books and dinner guests had the salutary effect of introducing this lonely youngster to a world of kindred spirits: the Frenchman René Descartes, who offered a theory for the recurring colors of the rainbow; the German Johannes Kepler, who discovered that a planet moved more slowly the farther away it was from the sun; and the Dutchman Christiaan Huygens, who gave the name *centrifugal force* to the ring-a-ring o'roses phenomenon young Newton had noticed a few years earlier.

Just that suddenly, Newton had the inklings of what it was like to feel normal. All his life, he had felt like an intruder, as if there were no place for him on this earth. Now, in the study of natural philosophy, he had found a home, a community of persons like himself, where he might be accepted, appreciated, possibly even loved.

During this time, Newton fell behind in his studies at school, so distracted was he by his newly adopted intellectual family. Also, it didn't help his concentration that he had become infatuated with Mr. Clarke's comely and kind stepdaughter Katherine—though he was too shy to express his feelings except through the toy furniture he made for her.

Indeed, it took a kick in the stomach from the girl's bully of a brother to awaken young Newton from his reverie and to coax him into scrapping his way to the head of the class. However, no sooner had he done so than his mother intruded once again; this time, she ordered him back to the manor.

The properties and responsibilities the Newtons had inherited from the late Reverend Smith had become too burdensome for her to manage alone. Besides, she remonstrated, her son had already received more than an adequate education; after all, neither his father nor any other Newton in history had even been able to write their own names.

Newton returned to Woolsthorpe, but he did so over the protests of his teacher and uncle. Not only was Newton now the school's top student, Stokes and the Reverend Ayscough pleaded, but by having earned that distinction so dramatically, the young man was quite possibly the first bona fide genius this rural county had ever produced.

The teenager now disliked his mother more than ever; he was openly disobedient and frightfully surly. As a symbol of his protest, the seventeen-year-old Newton purchased a small notebook: His body might be back in Woolsthorpe, he thought defiantly, but his mind would remain on natural philosophy, which required all its students to keep a careful journal of their theories and observations.

Unfortunately for Hanna Newton-Smith, but fortunately for science, her son proved to be inept at running a farm. One day, for example, he became so engrossed in a small water wheel he had built, he did not notice that a group of pigs had forded the stream and were eating the neighbor's corn.

His mother was fined "for suffering his swine to trespass in y^{e} corn fields," the court clerk wrote in the record, and "for suffering his fence belonging to his yards to be out of repair." That was not the first time Mrs. Newton-Smith had had to pay for her son's distractedness, but it was most certainly to be the last; forthwith, she sent him packing back to Grantham.

No sooner had young Newton returned to the Clarke household than he realized fully just how much he had missed not only his studies but the lovely Katherine. She herself gave many an indication of having similar feelings toward him—a gentle touch here, a kindly glance there—but all to no avail. So fearful was he about being rejected, Newton stopped short of ever confessing his romantic feelings to her.

The young man was much more aggressive when it came to his grammar schooling, finishing it in only nine months. On his last day, in the summer of 1661, Mr. Stokes bid him to stand before the class. As the young man obeyed, he and his classmates had the impression that a scolding was about to take place. There were furtive glances, whispers, and a lot of fidgeting. But why? What now! Newton wondered glumly.

Facing the class, expecting the worst, Newton was soon relieved of his anxiety. Mr. Stokes began praising him for being such a model student, entreating the others to be like this young man who, though orphaned, bullied, and badgered, had become the pride and joy of Lincolnshire County. Weeping, the devoted teacher delivered such a moving tribute to his prize pupil that even the young students seated at their desks had tears in their eyes when it was all over.

On the strength of enthusiastic recommendations from the Reverend Ayscough and Mr. Stokes, not to mention the merits of his own achievements, young Newton was readily accepted into Trinity College, the reverend's alma mater. It was, as he put it in a letter to his mother, "the famousest College" on the entire campus of Cambridge University, having been founded in 1546 by none other than King Henry VIII.

Objectively speaking, seventeenth-century Cambridge was little more than a dingy village, but to this young man from the country, it was the grandest place he had ever seen. By coincidence, it was also at its gayest in more than a decade.

Eleven years earlier, when the civil war had been decided in favor of Parliament, the puritanical victors had imposed on England unprecedentedly strict rules of behavior. They had made adultery a capital crime and outlawed nearly all manner of recreation, including horse racing, theater, and dancing round the Maypole. The Puritan rulers even had outlawed the celebration of Christmas, prompting one aghast Anglican to grouse: "Who would have thought to have seen in England the churches shut and the shops open on Christmas Day?"

By 1660, the English had had enough of being forced to live so austere an existence—of obeying the severe rules of some puritanical heavenly realm, as it were. They yearned for the more frolicsome rules of the delightfully imperfect earthly realm, whereupon they restored the sacred English crown to Charles II, the beheaded king's eldest son. Thus, in 1661, when Newton arrived in Cambridge, he found it in the midst of celebrating the country's return to a more secular existence, complete with parades, music, and rowdy fairs.

While England was loosening its hair, though, young Newton was obliged to tighten his belt. Mrs. Newton-Smith was more than wealthy enough to pay for her son's tuition, but she had decided to withhold her support, forcing the freshman to be enrolled into the college as a subsizar.

This was the name given to poor students who helped finance their education by being part-time servants to others whose parents fully supported them. For the next several years, therefore, Newton once again found himself being tormented by equals who felt superior to him; moreover, it would have been easier to withstand the abuse if, deep down inside, Newton himself had not felt inferior and unloved.

Instinctively the young man reverted to his old habits. Whenever he was not occupied with classes, church services, or his servile duties—which included emptying chamber pots, grooming his master’s hair, and hauling firewood—the insecure prodigy from Woolsthorpe immersed himself in the details of the natural world.

One evening, after finishing his subsizar’s chores in the kitchen at Trinity, he divided the heart of an eel into three sections. For hours, the young man stared and took careful notes, marveling at how the disconnected pieces continued to beat in synchrony.

Newton even began to experiment on his own eyes with harrowing carelessness. At one point, he wedged a flat stick “betwixt my eye & y^e bone as neare to y^e backside of my eye as I could,” coming dangerously close to blinding himself, all in the hopes of understanding exactly how humans perceive light and color. “Pressing my eye with the end of it … there appeared several white, darke & colored circles,” he noted casually, “which circles were plainest when I continued to rub my eye with y^e point of y^e bodkin.”

During his years at Trinity, his small notebooks, which he carried with him everywhere, came to be filled with the observations and queries of his powerful concentration and wide-ranging curiosity. “Of Light and Color,” “Of Gravity,” “Of God”—these were more than mere headings in this queer young man’s present investigations, they were glimpses at the voracious appetite of a rare and gifted mind.

While Newton’s brain sped onward, well nourished and full of energy, his body began to lag behind; in 1664, it gave out altogether. His ceaseless inquiries having deprived him of sleep for the better part of his undergraduate career, Newton was bedridden with exhaustion.

Though he felt weak for many months thereafter, the young man recovered in time to take his final exams. He did not perform well, but he earned his bachelor of arts degree. Moreover, influential professors who espied in this introverted and mediocre student the makings of a first-rate scholar intervened, and Newton was granted a scholarship to pursue a master’s degree.

He had hardly commenced his new course of studies when news reached Cambridge that the dreaded plague had invaded London. In the past twenty years, that city’s population had doubled, seriously compromising its medieval sanitary facilities. Now reports indicated that up to 13,000 people a week were dying.

Though Cambridge was more than forty miles away from all of that, officials decided anyway to close down the university, wishing to avoid a repetition of history: Back in the fourteenth century, the Black Death, as it was called, had spread like a pestilent wind all across Europe, turning Cambridge into a ghost town.

Before the formal order was given for students to evacuate the city, however, young Newton had returned to Woolsthorpe: Even his mother’s company was preferable to the risk of being killed by this horrific affliction. Anyway, he figured, it was time to reflect on all that he had learned during the past four years at Trinity.

It was the summer of 1665, and while hysteria and death roiled through the narrow streets of London, the twenty-two-year-old spent his days lounging in the garden, puzzling out the details of a new mathematics that would one day come to be called the *calculus*. Above all, he savored the solitude, his mother having long since given up on nagging him to become a gentleman farmer.

On one particular day, the weather was so agreeable and Newton was so immersed in thought, he did not notice it was getting late. Gradually the garden around him began to glow warmly, bathed with the soft golden light only a waning summer sun could produce.

Suddenly the thud of an apple falling from a nearby tree startled the young man out of his deep meditations. In the few moments it took for him to switch trains of thought, the top of a gigantic-looking full moon began to show itself above the eastern horizon.

Within minutes, young Newton's insatiable curiosity began to nibble away at the apple and the moon. Why did apples fall straight down to the earth's surface, rather than askance? What if the apple had started from higher up—a mile, a hundred miles, as high as the moon—would it still have fallen to the earth?

For that matter, didn't the moon itself feel the tug of earth's gravity? If so, would it not mean that the moon was under the sway of earthly influences, which contradicted the common belief that the moon existed within the heavenly realm, completely aloof from our planet?

Engaged by these heretical speculations, Newton persevered into the wee hours of the night. If the moon could feel the earth's tug, then why didn't it fall to the ground like an apple? No doubt, he conjectured, it was because Huygen's centrifugal force pulled the moon *away* from the earth; if that and the earth's pull balanced each other out, then perhaps that would explain how the moon was able to stay in its ring-a-ring o'roses orbit indefinitely.

Seated beneath the steely light of the moon, Newton was engrossed in his thoughts. More than that, while crickets chirped and frogs croaked in a nearby pond, the young man began to jot down certain ideas and calculations that would one day lead him to formulate his extraordinary equation of universal gravitation.

It would take more than twenty years before the world would learn of what had happened this night. It would take that long for Newton to perfect and publish his results, but when that day came, the heavens would fall to the ground with the thunderous boom of a million plummeting apples.

VIDI

Twenty-three centuries ago, Plato led a historic revolt against the traditional gods who lived atop Mt. Olympus. They were no longer praiseworthy, he complained, because they had become too mischievous, too immoral, and too undignified.

More than that, the famous Academician sniffed, those old gods were now too provincial for a Greek empire that had expanded dramatically under the Macedonian leadership of King Philip II (and soon would grow even larger under his son, Alexander the Great). Such a vast and victorious civilization needed—nay, merited—world-class divinities.

"A man may give what account he pleases of Zeus and Hera and the rest of the traditional pantheon," Plato intoned, but it was time for the Greek people to enlarge their religious horizons by looking heavenward, recognizing the "superior dignity of the visible gods, the heavenly bodies."

As if that were not enough to ask of his fellow countrymen, Plato went on to implore them to "cast off the superstitious fear of prying into the Divine … by setting ourselves to get a scientific knowledge of their [i.e., heavenly bodies'] motions and periods. Without this astronomical knowledge," he argued in sublime rhetorical fashion, "a city will never be governed with true statesmanship, and human life will never be truly happy."

Convincing the Greek people to adopt entirely new gods *plus* asserting that mere mortals were capable of comprehending godly behavior was a religious revolution of the most radical sort. It also was a *scientific* revolution, though this was not to be recognized fully until Isaac Newton's dramatic discovery in the seventeenth century.

That recognition was slow in coming, it turned out, because astronomers were slow to interpret correctly what they were seeing in the night sky. The sun, moon, and stars all behaved impeccably, they felt, always appearing to move in perfect circles around the earth; among all known curves, circles were considered godly, because they were flawlessly symmetric and, by virtue of their having no beginning and no end, eternal.

What befuddled astronomers were five spots of non-twinkling light that seemed to wander hither and yon across the night sky as if they were drunk. Plato was aghast: This erratic behavior was not godlike—indeed, it was redolent of Zeus's and Hera's outrageous shenanigans—and it threatened to discredit his religious reformation.

Greek astronomers soon began referring to these wayward deities as *planets*—the Greek word for vagabonds—and set upon trying to make sense out of their seemingly imperfect movements. It took them two decades, but the effort was well spent: Plato's religious revolution was rescued by a heroic exercise in circular reasoning.

Whereas the other heavenly bodies appeared to whiz around in imaginary circles, Plato and his colleagues explained, planets whizzed about with a great deal more freedom upon the surfaces of imaginary *globes*. Since globes were just as symmetric and seamlessly eternal as circles—in fact, mathematically speaking, globes were nothing but two-dimensional circles—planetary motion was no less divine than the motion of the moon, sun, and stars.

In the years following Plato's death in 347 B.C., Aristotle extended his mentor's incipient revolution even further. With extraordinary detail and fabulous logic, Aristotle now offered an explanation for how and why Plato's new celestial gods were superior to humans and everything else on earth.

All the heavenly bodies in the universe—the moon, sun, planets, and stars—revolved around the earth, which itself did not move in any way. Furthermore, Aristotle theorized, the universe was segregated into two distinct regions: The central one encompassed the earth and its atmosphere; beyond that—from the moon outwards—was what Aristotle referred to as the celestial region.

The *earthly* realm, Aristotle opined, consisted of only four essential qualities: wet and dry, hot and cold. They alone underlay everything terrestrial, including the four elements his contemporaries believed were the bases of physical reality. What they called Earth was essentially dry and cold; Water was cold and wet; Air was wet and hot; Fire was hot and dry.

The earthly realm was corruptible and changeable, Aristotle maintained, because the quartet of basic elements and their underlying four qualities were themselves corruptible and changeable. For example, if one heated Water, which was cold and wet, it became Air, which was hot and wet.

Furthermore, Aristotle explained, all four terrestrial elements tended to move in straight lines, which was entirely appropriate: Straight lines were the most earthly of all curves, because they had endpoints, symbolizing birth and death. For example, if not otherwise coerced, Earth and Water always opted to move straight *downward*, giving them an air of gravity. By contrast, Air and Fire appeared to possess an inherent levity, always preferring to move straight *upward*.

The *celestial* realm was another matter altogether. It consisted entirely of a fifth basic element, a quintessential protoplasm named Ether. This miraculous material came in different densities, Aristotle imagined, forming everything from the sun, moon, stars, and planets to a nested set of revolving globes upon whose invisible surfaces the heavenly bodies were whirled around in their flawless orbits.

The moon, sun, and stars were attached to globes that always spun in one direction, which explained their perfectly circular orbits. As for the celestial vagabonds, the planets, they were attached to globes that spun this way and that in an orderly but complicated fashion, which explained their more varied movements across the night sky.

Unlike the four earthly elements, Aristotle believed, Ether was incorruptible. Its flawlessness meant that the heavens would always remain perfect and unchanging; they never would rust or break down.

With this theory of the universe, Aristotle had fulfilled Plato's fondest wishes: He had given the earthly rabble their first peek at the privileged lifestyles of the celestial starlets, fresh-faced deities whose impeccable behavior was at once unassailable *and* comprehensible. People were quite thrilled at what they saw, furthermore, because Aristotle's universe was through and through a *cosmos*, the Greek word for orderliness, beauty, and decency—everything they could have hoped for in their new gods.

His theory also satisfied the Principle of Sufficient Reason, so dear to Western philosophy, which maintained that for every effect in the universe, there had to be a rational cause. For example, according to Aristotle, pieces of Earth fell downward because of a natural desire to be reunited with their primary source, the earth. Heavy objects fell faster than light ones, he supposed, because their desire was that much greater.

Aristotle even had a plausible and reverent explanation for what caused the huge heavenly globes to revolve. Each one, he explained, was swept around by an ethereal wind whipped up by the movement of the globe immediately above it, the outermost globe being impelled by the *Primum Mobile*, the prime mover, God Himself.

Plato had introduced religion and science to one another and had lived long enough to see the two engaged. Now Aristotle had married them in a most endearing and enduring way. Moreover, every indication was that this odd couple would benefit mutually from the unprecedented betrothal.

For its part, science painted a flattering picture of the heavens and corroborated the existence of a supreme god. Its down-to-earth explanations of an otherwise mysterious realm informed and enriched people's religious convictions, exactly as Plato had hoped: "The study we require to bring us to true piety," he had said, "is astronomy."

For its part, religion expanded the domain and elevated the reputation of science. Before this, to the extent that it was even definable, science had been widely regarded as an eccentric enterprise of doubtful value, preoccupied by the esoterics of the earthly realm and the abstractions of the mathematical realm.

As the centuries passed, however, so did the Greek empire and the fruits of its historic religious and scientific innovations. The rise of Christianity in the Western world became the newest religious revolution, during which many old earthly gods were exchanged for the one heavenly God worshipped by orthodox Jews and extolled by the recently martyred heretic, Jesus of Nazareth.

Since most people in the civilized world came to speak Latin, not Greek, they lived and died never even knowing about Aristotle, much less his theory of the universe. As the old Greek texts gradually were translated, however, Christians discovered that, as the Dominican St. Albert the Great enthused: "The sublimest wisdom of which the world could boast flourished in Greece. Even as the Jews knew God by the scriptures, so the pagan philosophers knew Him by the natural wisdom of reason, and were debtors to Him for it by their homage."

By the thirteenth century, students across Europe were beginning to learn all about Platonic rhetoric, Aristotelian logic, and Euclidean geometry; indeed, it became quite the fashion to do so. More significantly, Christian leaders were learning that the rabbi Maimonides had already reconciled Aristotle's cosmology with Judaism and that the philosopher Averroës had done the same with the religion of Islam.

Not to be left behind, therefore, the brilliant Dominican theologian St. Thomas Aquinas helped to accommodate Aristotle's geocentric universe to Christianity. There were myriad subtleties involved, but the upshot was that the heavenly bodies, no longer worshipped as demigods, were imagined to ride upon globes kept spinning by angels, not ethereal winds. Above all, Aristotle's *Primum Mobile* was identified with the one-and-only Judeo-Christian God, not just some generic divinity.

What Aristotle had first joined together and time and language differences had put asunder, Jews, Muslims, and now Christians had rejoined. Science and religion were in one another's arms yet again, and this time their honeymoon would last throughout a historic renaissance in Western civilization.

Beginning in the fourteenth century, however, much of the inhabited world was devastated by a succession of horrifying outbreaks of bubonic plague. Between the years 1347 and 1350 alone, it wiped out at least one-third of the European population.

In the aftermath, there was a great deal of finger-pointing: Survivors blamed their spiritual leaders for not having forewarned them of this apocalyptic rebuke from God. And in response, the clergy castigated the masses for inviting such punishment with their sinful behavior.

Ironically, Christian churches and monasteries all over Europe had been hit worse than the general laity; fully half of God's holiest were now dead, which regrettably led to an even greater calamity. As one observer noted: "Men whose wives had died of the pestilence flocked to Holy Orders of whom many were illiterate."

Lured by large sums of money offered by villages bereft of a religious leader, more and more men joined the priesthood for all the wrong reasons. Most of them were "arrogant, given to pomp," Pope Clement VI lashed out in disgust, wasting their ill-gotten wealth "on pimps and swindlers and neglecting the ways of God."

In this derelict and weakened condition, the Catholic church was pummeled by two of its most disillusioned members. In 1517, the German priest Martin Luther fathered a historic religious reformation by beseeching his colleagues to return to a Christianity sustained by childlike faith and good deeds, not by the extravagances of a temporal world. And in 1543, the Polish theologian Nicholas Copernicus touched off a religious-scientific revolution by urging a divorce from Aristotle; at the center of the universe was the sun, he claimed, not the earth.

Copernicus was an amateur astronomer, but he had no new observational evidence with which to defend his opinion. He simply believed that the geocentric theory was unnecessarily complicated, made so by the misguided presumption that we were looking at the heavens from some rock-steady vantage point smack in the middle of the action.

For example, Copernicus speculated, the movement of the vagabond planets appeared complicated only because we ourselves were moving through space in a complicated way, riding aboard an earth that was whirling on its axis like a ballerina as it revolved around the sun. Once we took those earthly motions into account, he demonstrated, the motion of the planets became sublimely circular, just like that of all the other heavenly bodies.

To a child being swung around by the arms, everything in the world appeared to wobble and spin. Were things really moving that way? The child's answer would be "no, of course not" only if he admitted to being the one who was spinning around, not they. Such was Copernicus's simple but stinging argument.

This Polish canon of Frauenburg, East Prussia, was not the first to have championed the heliocentric theory; 2,000 years earlier, a number of Greek philosophers had come up with several versions of the same idea. It had proven to be controversial back then, and for many of the same reasons, it turned out to be so again.

Scientifically speaking, the critics pointed out, it simply did not feel as if the earth were moving; if indeed it was whirling around the sun and spinning around on its axis, we would expect there to be some overt indication of it. Some astronomers even conjectured that everything would be flung off the earth's surface, like water droplets flying off a spinning wet wheel.

Religiously speaking, there were compelling objections as well. In Joshua 10:12–13, the Old Testament clearly stated that during the battle of Gibeon "the sun stood still, and the moon stayed, until the people had avenged themselves upon their enemies." Most who believed in the Judeo-Christian God took this to imply that, quite literally, under normal circumstances, the sun and moon *moved* around the earth.

In view of these and other objections, and because there was no physical evidence to favor the Copernican theory, most of the civilized world—religious and scientific—continued to believe in Aristotle's view of the heavens. Even fellow revolutionary Martin Luther ridiculed Copernicus for defending such an outlandish idea as heliocentricism. Still, it had been a revolutionary century, and before it was over, there appeared signs in the heavens that tended to absolve Copernicus.

The first omen came during one evening in 1572. A bright new star suddenly appeared in the sky (astronomers later believed it to be an exploding star, or supernova), causing people everywhere to look up in wonder. "A miracle indeed," a Danish astronomer named Tycho Brahe gushed, "the greatest of all that has occurred in the whole range of nature since the beginning of the world."

For Aristotle's theory, this miracle was a disaster, because it violated the theory's all-important premise that the heavens were permanent and incorruptible. Only in the earthly realm were things supposed to pass in and out of existence like that.

Five years later, a second omen compounded the disaster. This time it was a comet so bright it could be seen in daylight all over Europe. Amazing as it was, however, the astronomer Brahe was even more stunned when he measured the comet's parallax.

Parallax was an optical illusion that astronomers had found so useful it had become one of the tricks of their trade. When looking at an object, first with the right eye and then the left, an object appeared to shift position with respect to the background. Fortuitously, the amount of that shift, or parallax, *decreased as* the object's distance *increased*. (See it for yourself, by looking at your index finger from different distances.)

In the case of the comet, the right-eye view was provided by Brahe watching from an island off the coast of Denmark. The left-eye view, so to speak, was provided by his colleagues in Prague. The difference between the two views, the parallax, enabled Brahe to conclude that the comet was four times farther from us than the moon.

Astronomers were incredulous. Aristotle had said, and they had always believed, that comets were caused by fiery disturbances in the earth's atmosphere, existing not much farther up than ordinary clouds. For a comet to be streaking through the heavens, beyond the moon, was unthinkable.

On the face of it, therefore, the recent star and comet were unsightly blemishes on Aristotle's stellar reputation. Indeed, the only vindication Aristotle received during these fateful years was in regard to his belief that comets were harbingers of doom. On that score, unfortunately for his theory of the universe, he was absolutely right.

In the years ahead, as science became increasingly receptive to the possibility that Aristotle might be wrong, religion became more defensive toward dissenters of any kind. Luther's religious reformation had spawned a vast Protestant movement, and the

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