Great Physicists: The Life and Times of Leading Physicists from Galileo to Hawking

William H. Cropper

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Preface

This book tells about lives in science, specifically the lives of thirty from the pantheon of physics. Some of the names are familiar (Newton, Einstein, Curie, Heisenberg, Bohr), while others may not be (Clausius, Gibbs, Meitner, Dirac, Chandrasekhar). All were, or are, extraordinary human beings, at least as fascinating as their subjects. The short biographies in the book tell the stories of both the people and their physics.

The chapters are varied in format and length, depending on the (sometimes skimpy) biographical material available. Some chapters are equipped with short sections (entitled "Lessons") containing background information on topics in mathematics, physics, and chemistry for the uninformed reader.

Conventional wisdom holds that general readers are frightened of mathematical equations. I have not taken that advice, and have included equations in some of the chapters. Mathematical equations express the language of physics: you can't get the message without learning something about the language. That should be possible if you have a rudimentary (high school) knowledge of algebra, and, if required, you pay attention to the "Lessons" sections. The glossary and chronology may also prove helpful. For more biographical material, consult the works cited in the "Invitation to More Reading" section.

No claim is made that this is a comprehensive or scholarly study; it is intended as recreational reading for scientists and students of science (formal or informal). My modest hope is that you will read these chapters casually and for entertainment, and learn the lesson that science is, after all, a human endeavor.

William H. Cropper

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MECHANICS

Historical Synopsis

Physics builds from observations. No physical theory can succeed if it is not confirmed by observations, and a theory strongly supported by observations cannot be denied. For us, these are almost truisms. But early in the seventeenth century these lessons had not yet been learned. The man who first taught that observations are essential and supreme in science was Galileo Galilei.

Galileo first studied the motion of terrestrial objects, pendulums, free-falling balls, and projectiles. He summarized what he observed in the mathematical language of proportions. And he extrapolated from his experimental data to a great idealization now called the "inertia principle," which tells us, among other things, that an object projected along an infinite, frictionless plane will continue forever at a constant velocity. His observations were the beginnings of the science of motion we now call "mechanics."

Galileo also observed the day and night sky with the newly invented telescope. He saw the phases of Venus, mountains on the Moon, sunspots, and the moons of Jupiter. These celestial observations dictated a celestial mechanics that placed the Sun at the center of the universe. Church doctrine had it otherwise: Earth was at the center. The conflict between Galileo's telescope and Church dogma brought disaster to Galileo, but in the end the telescope prevailed, and the dramatic story of the confrontation taught Galileo's most important lesson.

Galileo died in 1642. In that same year, his greatest successor, Isaac Newton, was born. Newton built from Galileo's foundations a system of mechanics based on the concepts of mass, momentum, and force, and on three laws of motion. Newton also invented a mathematical language (the "fluxion" method, closely related to our present-day calculus) to express his mechanics, but in an odd historical twist, rarely applied that language himself.

Newton's mechanics had—and still has—cosmic importance. It applies to the motion of terrestrial objects, and beyond that to planets, stars, and galaxies. The grand unifying concept is Newton's theory of universal gravitation, based on the concept that all objects, small, large, and astronomical (with some exotic exceptions), attract one another with a force that follows a simple inverse-square law.

Galileo and Newton were the founders of modern physics. They gave us the rules of the game and the durable conviction that the physical world is comprehensible.

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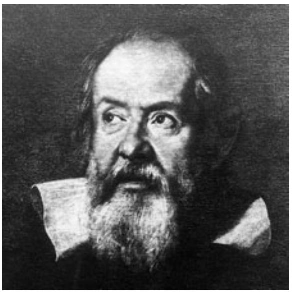
How the Heavens Go

Galileo Galilei



The Tale of the Tower

Legend has it that a young, ambitious, and at that moment frustrated mathematics professor climbed to the top of the bell tower in Pisa one day, perhaps in 1591, with a bag of ebony and lead balls. He had advertised to the university community at Pisa that he intended to disprove by experiment a doctrine originated by Aristotle almost two thousand years earlier: that objects fall at a rate proportional to their weight; a ten-pound ball would fall ten times faster than a one-pound ball. With a flourish the young professor signaled to the crowd of amused students and disapproving philosophy professors below, selected balls of the same material but with much different weights, and dropped them. Without air resistance (that is, in a vacuum), two balls of different weights (and made of any material) would have reached the ground at the same time. That did not happen in Pisa on that day in 1591, but Aristotle's ancient principle was clearly violated anyway, and that, the young professor told his audience, was the lesson. The students cheered, and the philosophy professors were skeptical.

The hero of this tale was Galileo Galilei. He did not actually conduct that "experiment" from the Tower of Pisa, but had he done so it would have been entirely in character. Throughout his life, Galileo had little regard for authority, and one of his perennial targets was Aristotle, the ultimate authority for university philosophy faculties at the time. Galileo's personal style was confrontational, witty, ironic, and often sarcastic. His intellectual style, as the Tower story instructs, was to build his theories with an ultimate appeal to observations.

The philosophers of Pisa were not impressed with either Galileo or his methods, and would not have been any more sympathetic even if they had witnessed the Tower experiment. To no one's surprise, Galileo's contract at the University of Pisa was not renewed.

Padua

But Galileo knew how to get what he wanted. He had obtained the Pisa post with the help of the Marquis Guidobaldo del Monte, an influential nobleman and competent mathematician. Galileo now aimed for the recently vacated chair of mathematics at the University of Padua, and his chief backer in Padua was Gianvincenzio Pinelli, a powerful influence in the cultural and intellectual life of Padua. Galileo followed Pinelli's advice, charmed the examiners, and won the approval of the Venetian senate (Padua was located in the Republic of Venice, about twenty miles west of the city of Venice). His inaugural lecture was a sensation.

Padua offered a far more congenial atmosphere for Galileo's talents and lifestyle than the intellectual backwater he had found in Pisa. In the nearby city of Venice, he found recreation and more—aristocratic friends. Galileo's favorite debating partner among these was Gianfrancesco Sagredo, a wealthy nobleman with an eccentric manner Galileo could appreciate. With his wit and flair for polemics, Galileo was soon at home in the city's salons. He took a mistress, Marina Gamba, described by one of Galileo's biographers, James Reston, Jr., as "hot-tempered, strapping, lusty and probably illiterate." Galileo and Marina had three children: two daughters, Virginia and Livia, and a son, Vincenzo. In later life, when tragedy loomed, Galileo found great comfort in the company of his elder daughter, Virginia.

During his eighteen years in Padua (1592–1610), Galileo made some of his most important discoveries in mechanics and astronomy. From careful observations, he formulated the "times-squared" law, which states that the vertical distance covered by an object in free fall or along an inclined plane is proportional to the square of the time of the fall. (In modern notation, the equation for free fall is expressed $s = \frac{gt^2}{2}$, with s and t the vertical distance and time of the fall, and g the acceleration of gravity.) He defined the laws of projected motion with a controlled version of the Tower experiment in which a ball rolled down an inclined plane on a table, then left the table horizontally or obliquely and dropped to the floor. Galileo found that he could make calculations that agreed approximately with his experiments by resolving projected motion into two components, one horizontal and the other vertical. The horizontal component was determined by the speed of the ball when it left the table, and was "conserved"—that is, it did not subsequently change. The vertical component, due to the ball's weight, followed the times-squared rule.

For many years, Galileo had been fascinated by the simplicity and regularity of pendulum motion. He was most impressed by the constancy of the pendulum's "period," that is, the time the pendulum takes to complete its back-and-forth cycle. If the pendulum's swing is less than about 30°, its period is, to a good approximation, dependent only on its length. (Another Galileo legend pictures him as a nineteen-year-old boy in church, paying little attention to the service, and timing with his pulse the swings of an oil lamp suspended on a wire from a high ceiling.) In Padua, Galileo confirmed the constant-period rule with experiments, and then uncovered some of the pendulum's more subtle secrets.

In 1609, word came to Venice that spectacle makers in Holland had invented an optical device—soon to be called a telescope—that brought distant objects much closer. Galileo immediately saw a shining opportunity. If he could build a prototype and demonstrate it to the Venetian authorities before Dutch entrepreneurs arrived on the scene, unprecedented rewards would follow. He knew enough about optics to guess that the Dutch design was a combination of a convex and a concave lens, and he and his instrument maker had the exceptional skill needed to grind the lenses. In twenty-four hours, according to Galileo's own account, he had a telescope of better quality than any produced by the Dutch artisans. Galileo could have demanded, and no doubt received, a large sum for his invention. But fame and influence meant more to him than money. In an elaborate ceremony, he gave an eight-power telescope to Niccolò Contarini, the doge of Venice. Reston, in *Galileo,* paints this picture of the presentation of the telescope: "a celebration of Venetian genius, complete with brocaded advance men, distinguished heralds and secret operatives. Suddenly, the tube represented the flowering of Paduan learning." Galileo was granted a large bonus, his salary was doubled, and he was reappointed to his faculty position for life.

Then Galileo turned his telescope to the sky, and made some momentous, and as it turned out fateful, discoveries. During the next several years, he observed the mountainous surface of the Moon, four of the moons of Jupiter, the phases of Venus, the rings of Saturn (not quite resolved by his telescope), and sunspots. In 1610, he published his observations in *The Starry Messenger*, which was an immediate sensation, not only in Italy but throughout Europe.

But Galileo wanted more. He now contrived to return to Tuscany and Florence, where he had spent most of his early life. The grand duke of Tuscany was the young Cosimo de Medici, recently one of Galileo's pupils. To further his cause, Galileo dedicated *The Starry Messenger* to the grand duke and named the four moons of Jupiter the Medicean satellites. The flattery had its intended effect. Galileo soon accepted an astonishing offer from Florence: a salary equivalent to that of the highest-paid court official, no lecturing duties—in fact, no duties of any kind—and the title of chief mathematician and philosopher for the grand duke of Tuscany. In Venice and Padua, Galileo left behind envy and bitterness.

Florence and Rome

Again the gregarious and witty Galileo found intellectual companions among the nobility. Most valued now was his friendship with the young, talented, and skeptical Filippo Salviati. Galileo and his students were regular visitors at Salviati's beautiful villa fifteen miles from Florence. But even in this idyll Galileo was restless. He had one more world to conquer: Rome—that is, the Church. In 1611, Galileo proposed to the grand duke's secretary of state an official visit to Rome in which he would demonstrate his telescopes and impress the Vatican with the importance of his astronomical discoveries.

This campaign had its perils. Among Galileo's discoveries was disturbing evidence against the Church's doctrine that Earth was the center of the universe. The Greek astronomer and mathematician Ptolemy had advocated this cosmology in the second century, and it had long been Church dogma. Galileo could see in his observations evidence that the motion of Jupiter's moons centered on Jupiter, and, more troubling, in the phases of Venus that the motion of that planet centered on the Sun. In the sixteenth century, the Polish astronomer Nicolaus Copernicus had proposed a cosmology that placed the Sun at the center of the universe. By 1611, when he journeyed to Rome, Galileo had become largely converted to Copernicanism. Holy Scripture also regarded the Moon and the Sun as quintessentially perfect bodies; Galileo's telescope had revealed mountains and valleys on the Moon and spots on the Sun.

But in 1611 the conflict between telescope and Church was temporarily submerged, and Galileo's stay was largely a success. He met with the autocratic Pope Paul V and received his blessing and support. At that time and later, the intellectual power behind the papal throne was Cardinal Robert Bellarmine. It was his task to evaluate Galileo's claims and promulgate an official position. He, in turn, requested an opinion from the astronomers and mathematicians at the Jesuit Collegio Romano, who reported doubts that the telescope really revealed mountains on the Moon, but more importantly, trusted the telescope's evidence for the phases of Venus and the motion of Jupiter's moons.

Galileo found a new aristocratic benefactor in Rome. He was Prince Frederico Cesi, the founder and leader of the "Academy of Lynxes," a secret society whose members were "philosophers who are eager for real knowledge, and who will give themselves to the study of nature, and especially to mathematics." The members were young, radical, and, true to the lynx metaphor, sharp-eyed and ruthless in their treatment of enemies. Galileo was guest of honor at an extravagant banquet put on by Cesi, and shortly thereafter was elected as one of the Lynxes.

Galileo gained many influential friends in Rome and Florence—and, inevitably, a few dedicated enemies. Chief among those in Florence was Ludovico della Colombe, who became the self-appointed leader of Galileo's critics. *Colombe* means "dove" in Italian. Galileo expressed his contempt by calling Colombe and company the "Pigeon League."

Late in 1611, Colombe, whose credentials were unimpressive, went on the attack and challenged Galileo to an intellectual duel: a public debate on the theory of floating bodies, especially ice. A formal challenge was delivered to Galileo by a Pisan professor, and Galileo cheerfully responded, "Ever ready to learn from anyone, I should take it as a favor to converse with this friend of yours and reason about the subject." The site of the debate was the Pitti Palace. In the audience were two cardinals, Grand Duke Cosimo, and Grand Duchess Christine, Cosimo's mother. One of the cardinals was Maffeo Barberini, who would later become Pope Urban VIII and play a major role in the final act of the Galileo drama.

In the debate, Galileo took the view that ice and other solid bodies float because they are lighter than the liquid in which they are immersed. Colombe held to the Aristotelian position that a thin, flat piece of ice floats in liquid water because of its peculiar shape. As usual, Galileo built his argument with demonstrations. He won the audience, including Cardinal Barberini, when he showed that pieces of ebony, even in very thin shapes, always sank in water, while a block of ice remained on the surface.

The Gathering Storm

The day after his victory in the debate, Galileo became seriously ill, and he retreated to Salviati's villa to recuperate. When he had the strength, Galileo summarized in a treatise his views on floating bodies, and, with Salviati, returned to the study of sunspots. They mapped the motion of large spots as the spots traveled across the sun's surface near the equator from west to east.

Then, in the spring of 1612, word came that Galileo and Salviati had a competitor. He called himself Apelles. (He was later identified as Father Christopher Scheiner, a Jesuit professor of mathematics in Bavaria.) To Galileo's dismay, Apelles claimed that his observations of sunspots were the first, and explained the spots as images of stars passing in front of the sun. Not only was the interloper encroaching on Galileo's priority claim, but he was also broadcasting a false interpretation of the spots. Galileo always had an inclination to paranoia, and it now had the upper hand. He sent a series of bold letters to Apelles through an intermediary, and agreed with Cesi that the letters should be published in Rome by the Academy of Lynxes. In these letters Galileo asserted for the first time his adherence to the Copernican cosmology. As evidence he recalled his observations of the planets: "I tell you that [Saturn] also, no less than the horned Venus agrees admirably with the great Copernican system. Favorable winds are now blowing on that system. Little reason remains to fear crosswinds and shadows on so bright a guide."

Galileo soon had another occasion to proclaim his belief in Copernicanism. One of his disciples, Benedetto Castelli, occupied Galileo's former post, the chair of mathematics at Pisa. In a letter to Galileo, Castelli wrote that recently he had had a disturbing interview with the pious Grand Duchess Christine. "Her Ladyship began to argue against me by means of the Holy Scripture," Castelli wrote. Her particular concern was a passage from the Book of Joshua that tells of God commanding the Sun to stand still so Joshua's retreating enemies could not escape into the night. Did this not support the doctrine that the Sun moved around Earth and deny the Copernican claim that Earth moved and the Sun was stationary?

Galileo sensed danger. The grand duchess was powerful, and he feared that he was losing her support. For the first time he openly brought his Copernican views to bear on theological issues. First he wrote a letter to Castelli. It was sometimes a mistake, he wrote, to take the words of the Bible literally. The Bible had to be interpreted in such a way that there was no contradiction with direct observations: "The task of wise interpreters is to find true meanings of scriptural passages that will agree with the evidence of sensory experience." He argued that God could have helped Joshua just as easily under the Copernican cosmology as under the Ptolemaic.

The letter to Castelli, which was circulated and eventually published, brought no critical response for more than a year. In the meantime, Galileo took more drastic measures. He expanded the letter, emphasizing the primacy of observations over doctrine when the two were in conflict, and addressed it directly to Grand Duchess Christine. "The primary purpose of the Holy Writ is to worship God and save souls," he wrote. But "in disputes about natural phenomena, one must not begin with the authority of scriptural passages, but with sensory experience and necessary demonstrations." He recalled that Cardinal Cesare Baronius had once said, "The Bible tells us how to go to Heaven, not how the heavens go."

The first attack on Galileo from the pulpit came from a young Dominican priest named Tommaso Caccini, who delivered a furious sermon centering on the miracle of Joshua, and the futility of understanding such grand events without faith in established doctrine. This was a turning point in the Galileo story. As Reston puts it: "Italy's most famous scientist, philosopher to the Grand Duke of Tuscany, intimate of powerful cardinals in Rome, stood accused publicly of heresy from an important pulpit, by a vigilante of the faith." Caccini and Father Niccolò

Lorini, another Dominican priest, now took the Galileo matter to the Roman Inquisition, presenting as evidence for heresy the letter to Castelli.

Galileo could not ignore these events. He would have to travel to Rome and face the inquisitors, probably influenced by Cardinal Bellarmine, who had, four years earlier, reported favorably on Galileo's astronomical observations. But once again Galileo was incapacitated for months by illness. Finally, in late 1615 he set out for Rome.

As preparation for the inquisitors, a Vatican commission had examined the Copernican doctrine and found that its propositions, such as placing the Sun at the center of the universe, were "foolish and absurd and formally heretical." On February 25, 1616, the Inquisition met and received instructions from Pope Paul to direct Galileo not to teach or defend or discuss Copernican doctrine. Disobedience would bring imprisonment.

In the morning of the next day, Bellarmine and an inquisitor presented this injunction to Galileo orally. Galileo accepted the decision without protest and waited for the formal edict from the Vatican. That edict, when it came a few weeks later, was strangely at odds with the judgment delivered earlier by Bellarmine. It did not mention Galileo or his publications at all, but instead issued a general restriction on Copernicanism: "It has come to the knowledge of the Sacred Congregation that the false Pythagorean doctrine, namely, concerning the movement of the Earth and immobility of the Sun, taught by Nicolaus Copernicus, and altogether contrary to the Holy Scripture, is already spread about and received by many persons. Therefore, lest any opinion of this kind insinuate itself to the detriment of Catholic truth, the Congregation has decreed that the works of Nicolaus Copernicus be suspended until they are corrected."

Galileo, always an optimist, was encouraged by this turn of events. Despite Bellarmine's strict injunction, Galileo had escaped personal censure, and when the "corrections" to Copernicus were spelled out they were minor. Galileo remained in Rome for three months, and found occasions to be as outspoken as ever. Finally, the Tuscan secretary of state advised him not to "tease the sleeping dog further," adding that there were "rumors we do not like."

Comets, a Manifesto, and a Dialogue

In Florence again, Galileo was ill and depressed during much of 1617 and 1618. He did not have the strength to comment when three comets appeared in the night sky during the last four months of 1618. He was stirred to action, however, when Father Horatio Grassi, a mathematics professor at the Collegio Romano and a gifted scholar, published a book in which he argued that the comets provided fresh evidence against the Copernican cosmology. At first Galileo was too weak to respond himself, so he assigned the task to one of his disciples, Mario Guiducci, a lawyer and graduate of the Collegio Romano. A pamphlet, *Discourse on Comets*, was published under Guiducci's name, although the arguments were clearly those of Galileo.

This brought a worthy response from Grassi, and in 1621 and 1622 Galileo was sufficiently provoked and healthy to publish his eloquent manifesto, *The Assayer*. Here Galileo proclaimed, "Philosophy is written in this grand book the universe, which stands continually open to our gaze. But the book cannot be understood unless one first learns to comprehend the language and to read the alphabet in which it is composed. It is written in the language of mathematics, and its characters are triangles, circles and other geometric figures, without which it is humanly impossible to understand a single word of it; without these, one wanders about in a dark labyrinth."

The Assayer received Vatican approval, and Cardinal Barberini, who had supported Galileo in his debate with della Colombe, wrote in a friendly and reassuring letter, "We are ready to serve you always." As it turned out, Barberini's good wishes could hardly have been more opportune. In 1623, he was elected pope and took the name Urban VIII.

After recovering from a winter of poor health, Galileo again traveled to Rome in the spring of 1624. He now went bearing microscopes. The original microscope design, like that of the telescope, had come from Holland, but Galileo had greatly improved the instrument for scientific uses. Particularly astonishing to the Roman cognoscenti were magnified images of insects.

Shortly after his arrival in Rome, Galileo had an audience with the recently elected Urban VIII. Expecting the former Cardinal Barberini again to promise support, Galileo found to his dismay a different persona. The new pope was autocratic, given to nepotism, long-winded, and obsessed with military campaigns. Nevertheless, Galileo left Rome convinced that he still had a clear path. In a letter to Cesi he wrote, "On the question of Copernicus His Holiness said that the Holy Church had not condemned, nor would condemn his opinions as heretical, but only rash. So long as it is not demonstrated as true, it need not be feared."

Galileo's strategy now was to present his arguments hypothetically, without claiming absolute truth. His literary device was the dialogue. He created three characters who would debate the merits of the Copernican and Aristotelian systems, but ostensibly the debate would have no resolution. Two of the characters were named in affectionate memory of his Florentine and Venetian friends, Gianfrancesco Sagredo and Filippo Salviati, who had both died. In the dialogue Salviati speaks for Galileo, and Sagredo as an intelligent layman. The third character is an Aristotelian, and in Galileo's hands earns his name, Simplicio.

The dialogue, with the full title *Dialogue Concerning the Two Chief World Systems*, occupied Galileo intermittently for five years, between 1624 and 1629. Finally, in 1629, it was ready for publication and Galileo traveled to Rome to expedite approval by the Church. He met with Urban and came away convinced that there were no serious obstacles.

Then came some alarming developments. First, Cesi died. Galileo had hoped to have his *Dialogue* published by Cesi's Academy of Lynxes, and had counted on Cesi as his surrogate in Rome. Now with the death of Cesi, Galileo did not know where to turn. Even more alarming was an urgent letter from Castelli advising him to publish the *Dialogue* as soon as possible in Florence. Galileo agreed, partly because at the time Rome and Florence were isolated by an epidemic of bubonic plague. In the midst of the plague, Galileo found a printer in Florence, and the printing was accomplished. But approval by the Church was not granted for two years, and when the *Dialogue* was finally published it contained a preface and conclusion written by the Roman Inquisitor. At first, the book found a sympathetic audience. Readers were impressed by Galileo's accomplished use of the dialogue form, and they found the dramatis personae, even the satirical Simplicio, entertaining.

In August 1632, Galileo's publisher received an order from the Inquisition to cease printing and selling the book. Behind this sudden move was the wrath of

Urban, who was not amused by the clever arguments of Salviati and Sagredo, and the feeble responses of Simplicio. He even detected in the words of Simplicio some of his own views. Urban appointed a committee headed by his nephew, Cardinal Francesco Barberini, to review the book. In September, the committee reported to Urban and the matter was handed over to the Inquisition.

Trial

After many delays—Galileo was once again seriously ill, and the plague had returned—Galileo arrived in Rome in February 1633 to defend himself before the Inquisition. The trial began on April 12. The inquisitors focused their attention on the injunction Bellarmine had issued to Galileo in 1616. Francesco Niccolini, the Tuscan ambassador to Rome, explained it this way to his office in Florence: "The main difficulty consists in this: these gentlemen [the inquisitors] maintain that in 1616 he [Galileo] was commanded neither to discuss the question of the earth's motion nor to converse about it. He says, to the contrary, that these were not the terms of the injunction, which were that that doctrine was not to be held or defended. He considers that he has the means of justifying himself since it does not appear at all from his book that he holds or defends the doctrine . . . or that he regards it as a settled question." Galileo offered in evidence a letter from Bellarmine, which bolstered his claim that the inquisitors' strict interpretation of the injunction was not valid.

Historians have argued about the weight of evidence on both sides, and on a strictly legal basis, concluded that Galileo had the stronger case. (Among other things, the 1616 injunction had never been signed or witnessed.) But for the inquisitors, acquittal was not an option. They offered what appeared to be a reasonable settlement: Galileo would admit wrongdoing, submit a defense, and receive a light sentence. Galileo agreed and complied. But when the sentence came on June 22 it was far harsher than anything he had expected: his book was to be placed on the Index of Prohibited Books, and he was condemned to life imprisonment.

Last Act

Galileo's friends always vastly outnumbered his enemies. Now that he had been defeated by his enemies, his friends came forward to repair the damage. Ambassador Niccolini managed to have the sentence commuted to custody under the Archbishop Ascanio Piccolomini of Siena. Galileo's "prison" was the archbishop's palace in Siena, frequented by poets, scientists, and musicians, all of whom arrived to honor Galileo. Gradually his mind returned to the problems of science, to topics that were safe from theological entanglements. He planned a dialogue on "two new sciences," which would summarize his work on natural motion (one science) and also address problems related to the strengths of materials (the other science). His three interlocutors would again be named Salviati, Sagredo, and Simplicio, but now they would represent three ages of the author: Salviati, the wise Galileo in old age; Sagredo, the Galileo of the middle years in Padua; and Simplicio, a youthful Galileo.

But Galileo could not remain in Siena. Letters from his daughter Virginia, now Sister Maria Celeste in the convent of St. Matthew in the town of Arcetri, near Florence, stirred deep memories. Earlier he had taken a villa in Arcetri to be near

Virginia and his other daughter, Livia, also a sister at the convent. He now appealed to the pope for permission to return to Arcetri. Eventually the request was granted, but only after word had come that Maria Celeste was seriously ill, and more important, after the pope's agents had reported that the heretic's comfortable "punishment" in Siena did not fit the crime. The pope's edict directed that Galileo return to his villa and remain guarded there under house arrest.

Galileo took up residence in Arcetri in late 1633, and for several months attended Virginia in her illness. She did not recover, and in the spring of 1634, she died. For Galileo this was almost the final blow. But once again work was his restorative. For three years he concentrated on his *Discourses on Two New Sciences*. That work, his final masterpiece, was completed in 1637, and in 1638 it was published (in Holland, after the manuscript was smuggled out of Italy). By this time Galileo had gone blind. Only grudgingly did Urban permit Galileo to travel the short distance to Florence for medical treatment.

But after all he had endured, Galileo never lost his faith. "Galileo's own conscience was clear, both as Catholic and as scientist," Stillman Drake, a contemporary science historian, writes. "On one occasion he wrote, almost in despair, that he felt like burning all his work in science; but he never so much as thought of turning his back on his faith. The Church turned its back on Galileo, and has suffered not a little for having done so; Galileo blamed only some wrong-headed individuals in the Church for that."

Methods

Galileo's mathematical equipment was primitive. Most of the mathematical methods we take for granted today either had not been discovered or had not come into reliable use in Galileo's time. He did not employ algebraic symbols or equations, or, except for tangents, the concepts of trigonometry. His numbers were always expressed as positive integers, never as decimals. Calculus, discovered later by Newton and Gottfried Leibniz, was not available. To make calculations he relied on ratios and proportionalities, as defined in Euclid's *Elements*. His reasoning was mostly geometric, also learned from Euclid.

Galileo's mathematical style is evident in his many theorems on uniform and accelerated motion; here a few are presented and then "modernized" through translation into the language of algebra. The first theorem concerns uniform motion:

> If a moving particle, carried uniformly at constant speed, traverses two distances, the time intervals required are to each other in the ratio of these distances.

For us (but not for Galileo) this theorem is based on the algebraic equation $s = vt$, in which s represents distance, v speed, and t time. This is a familiar calculation. For example, if you travel for three hours ($t = 3$ hours) at sixty miles per hour ($v = 60$ miles per hour), the distance you have covered is 180 miles ($s = 3 \times 60 = 180$ miles). In Galileo's theorem, we calculate two distances, call them s_1 and s_2, for two times, t_1 and t_2, at the same speed, v. The two calculations are

$$s_1 = vt_1 \text{ and } s_2 = vt_2$$

Dividing the two sides of these equations into each other, we get the ratio of Galileo's theorem,

$$\frac{t_1}{t_2} = \frac{s_1}{s_2}.$$

Here is a more complicated theorem, which does not require that the two speeds be equal:

> If two particles are moved at a uniform rate, but with unequal speeds, through unequal distances, then the ratio of time intervals occupied will be the product of the ratio of the distances by the inverse ratio of the speeds.

In this theorem, there are two different speeds, v_1 and v_2, involved, and the two equations are

$$s_1 = v_1 t_1 \text{ and } s_2 = v_2 t_2.$$

Dividing both sides of the equations into each other again, we have

$$\frac{s_1}{s_2} = \frac{v_1}{v_2}\frac{t_1}{t_2}.$$

To finish the proof of the theorem, we multiply both sides of this equation by $\frac{v_2}{v_1}$ and obtain

$$\frac{t_1}{t_2} = \frac{s_1}{s_2}\frac{v_2}{v_1}.$$

On the right side now is a product of the direct ratio of the distances $\frac{s_1}{s_2}$ and the inverse ratio of the speeds $\frac{v_2}{v_1}$, as required by the theorem.

These theorems assume that any speed v is constant; that is, the motion is not accelerated. One of Galileo's most important contributions was his treatment of uniformly accelerated motion, both in free fall and down inclined planes. "Uniformly" here means that the speed changes by equal amounts in equal time intervals. If the uniform acceleration is represented by a, the change in the speed v in time t is calculated with the equation $v = at$. For example, if you accelerate your car at the uniform rate $a = 5$ miles per hour per second for $t = 10$ seconds, your final speed will be $v = 5 \times 10 = 50$ miles per hour. A second equation, $s = \frac{at^2}{2}$, calculates s, the distance covered in time t under the uniform acceleration a. This equation is not so familiar as the others mentioned. It is most easily justified with the methods of calculus, as will be demonstrated in the next chapter.

The motion of a ball of any weight dropping in free fall is accelerated in the vertical direction, that is, perpendicular to Earth's surface, at a rate that is conventionally represented by the symbol g, and is nearly the same anywhere on Earth. For the case of free fall, with $a = g$, the last two equations mentioned are $v = gt$, for the speed attained in free fall in the time t, and $s = \frac{gt^2}{2}$ for the corresponding distance covered.

Galileo did not use the equation $s = \frac{gt^2}{2}$, but he did discover through experimental observations the times-squared (t^2) part of it. His conclusion is expressed in the theorem,

> The spaces described by a body falling from rest with a uniformly accelerated motion are to each other as the squares of the time intervals employed in traversing these distances.

Our modernized proof of the theorem begins by writing the free-fall equation twice,

$$s_1 = \frac{gt_1^2}{2} \text{ and } s_2 = \frac{gt_2^2}{2},$$

and combining these two equations to obtain

$$\frac{s_1}{s_2} = \frac{t_1^2}{t_2^2}.$$

In addition to his separate studies of uniform and accelerated motion, Galileo also treated a composite of the two in projectile motion. He proved that the trajectory followed by a projectile is parabolic. Using a complicated geometric method, he developed a formula for calculating the dimensions of the parabola followed by a projectile (for example, a cannonball) launched upward at any angle of elevation. The formula is cumbersome compared to the trigonometric method we use today for such calculations, but no less accurate. Galileo demonstrated the use of his method by calculating with remarkable precision a detailed table of parabola dimensions for angles of elevation from 1° to 89°.

In contrast to his mathematical methods, derived mainly from Euclid, Galileo's experimental methods seem to us more modern. He devised a system of units that parallels our own and that served him well in his experiments on pendulum motion. His measure of distance, which he called a *punto*, was equivalent to 0.094 centimeter. This was the distance between the finest divisions on a brass rule. For measurements of time he collected and weighed water flowing from a container at a constant rate of about three fluid ounces per second. He recorded weights of water in grains (1 ounce = 480 grains), and defined his time unit, called a *tempo*, to be the time for 16 grains of water to flow, which was equivalent to 1/92 second. These units were small enough so Galileo's measurements of distance and time always resulted in large numbers. That was a necessity because decimal numbers were not part of his mathematical equipment; the only way he could add significant digits in his calculations was to make the numbers larger.

Legacy

Galileo took the metaphysics out of physics, and so begins the story that will unfold in the remaining chapters of this book. As Stephen Hawking writes, "Galileo, perhaps more than any single person, was responsible for the birth of modern science. . . . Galileo was one of the first to argue that man could hope to understand how the world works, and, moreover, that he could do this by observing the real world." No practicing physicist, or any other scientist for that matter, can do his or her work without following this Galilean advice.

I have already mentioned many of Galileo's specific achievements. His work in mechanics is worth sketching again, however, because it paved the way for his greatest successor. (Galileo died in January 1642. On Christmas Day of that same year, Isaac Newton was born.) Galileo's mechanics is largely concerned with bodies moving at constant velocity or under constant acceleration, usually that of gravity. In our view, the theorems that define his mechanics are based on the equations $v = gt$ and $s = \frac{gt^2}{2}$, but Galileo did not write these, or any other, algebraic equations; for his numerical calculations he invoked ratios and proportionality. He saw that projectile motion was a resultant of a vertical component governed by the acceleration of gravity and a constant horizontal component given to the projectile when it was launched. This was an early recognition that physical quantities with direction, now called "vectors," could be resolved into rectangular components.

I have mentioned, but not emphasized, another building block of Galileo's mechanics, what is now called the "inertia principle." In one version, Galileo put it this way: "Imagine any particle projected along a horizontal plane without friction; then we know . . . that this particle will move along this plane with a motion which is uniform and perpetual, provided the plane has no limits." This statement reflects Galileo's genius for abstracting a fundamental idealization from real behavior. If you give a real ball a push on a real horizontal plane, it will not continue its motion perpetually, because neither the ball nor the plane is perfectly smooth, and sooner or later the ball will stop because of frictional effects. Galileo neglected all the complexities of friction and obtained a useful postulate for his mechanics. He then applied the postulate in his treatment of projectile motion. When a projectile is launched, its horizontal component of motion is constant in the absence of air resistance, and remains that way, while the vertical component is influenced by gravity.

Galileo's mechanics did not include definitions of the concepts of force or energy, both of which became important in the mechanics of his successors. He had no way to measure these quantities, so he included them only in a qualitative way. Galileo's science of motion contains most of the ingredients of what we now call "kinematics." It shows us how motion occurs without defining the forces that control the motion. With the forces included, as in Newton's mechanics, kinematics becomes "dynamics."

All of these specific Galilean contributions to the science of mechanics were essential to Newton and his successors. But transcending all his other contributions was Galileo's unrelenting insistence that the success or failure of a scientific theory depends on observations and measurements. Stillman Drake leaves us with this trenchant synopsis of Galileo's scientific contributions: "When Galileo was born, two thousand years of physics had not resulted in even rough measurements of actual motions. It is a striking fact that the history of each science shows continuity back to its first use of measurement, before which it exhibits no ancestry but metaphysics. That explains why Galileo's science was stoutly opposed by nearly every philosopher of his time, he having made it as nearly free from metaphysics as he could. That was achieved by measurements, made as precisely as possible with means available to Galileo or that he managed to devise."

2 A Man Obsessed

Isaac Newton

Continual Thought

In his later years, Isaac Newton was asked how he had arrived at his theory of universal gravitation. "By thinking on it continually," was his matter-of-fact response. "Continual thinking" for Newton was almost beyond mortal capacity. He could abandon himself to his studies with a passion and ecstasy that others experience in love affairs. The object of his study could become an obsession, possessing him nonstop, and leaving him without food or sleep, beyond fatigue, and on the edge of breakdown.

The world Newton inhabited in his ecstasy was vast. Richard Westfall, Newton's principal biographer in this century, describes this "world of thought": "Seen from afar, Newton's intellectual life appears unimaginably rich. He embraced nothing less than the whole of natural philosophy [science], which he explored from several vantage points, ranging all the way from mathematical physics to alchemy. Within natural philosophy, he gave new direction to optics, mechanics, and celestial dynamics, and he invented the mathematical tool [calculus] that has enabled modern science further to explore the paths he first blazed. He sought as well to plumb the mind of God and His eternal plan for the world and humankind as it was presented in the biblical prophecies."

But, after all, Newton was human. His passion for an investigation would fade, and without synthesizing and publishing the work, he would move on to another grand theme. "What he thought on, he thought on continually, which is to say exclusively, or nearly exclusively," Westfall continues, but "[his] career was episodic." To build a coherent whole, Newton sometimes revisited a topic several times over a period of decades.

Woolsthorpe

Newton was born on Christmas Day, 1642, at Woolsthorpe Manor, near the Lincolnshire village of Colsterworth, sixty miles northwest of Cambridge and one hundred miles from London. Newton's father, also named Isaac, died three months before his son's birth. The fatherless boy lived with his mother, Hannah, for three years. In 1646, Hannah married Barnabas Smith, the elderly rector of North Witham, and moved to the nearby rectory, leaving young Isaac behind at Woolsthorpe to live with his maternal grandparents, James and Mary Ayscough. Smith was prosperous by seventeenth-century standards, and he compensated the Ayscoughs by paying for extensive repairs at Woolsthorpe.

Newton appears to have had little affection for his stepfather, his grandparents, his half-sisters and half-brother, or even his mother. In a self-imposed confession of sins, made after he left Woolsthorpe for Cambridge, he mentions "Peevishness with my mother," "with my sister," "Punching my sister," "Striking many," "Threatning my father and mother Smith to burne them and the house over them," "wishing death and hoping it to some."

In 1653, Barnabas Smith died, Hannah returned to Woolsthorpe with the three Smith children, and two years later Isaac entered grammar school in Grantham, about seven miles from Woolsthorpe. In Grantham, Newton's genius began to emerge, but not at first in the classroom. In modern schools, scientific talent is often first glimpsed as an outstanding aptitude in mathematics. Newton did not have that opportunity; the standard English grammar school curriculum of the time offered practically no mathematics. Instead, he displayed astonishing mechanical ingenuity. William Stukely, Newton's first biographer, tells us that he quickly grasped the construction of a windmill and built a working model, equipped with an alternate power source, a mouse on a treadmill. He constructed a cart that he could drive by turning a crank. He made lanterns from "crimpled paper" and attached them to the tails of kites. According to Stukely, this stunt "Wonderfully affrighted all the neighboring inhabitants for some time, and caus'd not a little discourse on market days, among the country people, when over their mugs of ale."

Another important extracurricular interest was the shop of the local apothecary, remembered only as "Mr. Clark." Newton boarded with the Clark family, and the shop became familiar territory. The wonder of the bottles of chemicals on the shelves and the accompanying medicinal formulations would help direct him to later interests in chemistry, and beyond that to alchemy.

With the completion of the ordinary grammar school course of studies, Newton reached a crossroads. Hannah felt that he should follow in his father's footsteps and manage the Woolsthorpe estate. For that he needed no further education, she insisted, and called him home. Newton's intellectual promise had been noticed, however. Hannah's brother, William Ayscough, who had attended Cambridge, and the Grantham schoolmaster, John Stokes, both spoke persuasively on Newton's behalf, and Hannah relented. After nine months at home with her restless son, Hannah no doubt recognized his ineptitude for farm management. It probably helped also that Stokes was willing to waive further payment of the forty-shilling fee usually charged for nonresidents of Grantham. Having passed this crisis, Newton returned in 1660 to Grantham and prepared for Cambridge.

Cambridge

Newton entered Trinity College, Cambridge, in June 1661, as a "subsizar," meaning that he received free board and tuition in exchange for menial service. In the Cambridge social hierarchy, sizars and subsizars were on the lowest level. Evidently Hannah Smith could have afforded better for her son, but for some reason (possibly parsimony) chose not to make the expenditure.

With his lowly status as a subsizar, and an already well developed tendency to introversion, Newton avoided his fellow students, his tutor, and most of the Cambridge curriculum (centered largely on Aristotle). Probably with few regrets, he went his own way. He began to chart his intellectual course in a "Philosophical Notebook," which contained a section with the Latin title *Quaestiones quaedam philosophicam* (Certain Philosophical Questions) in which he listed and discussed the many topics that appealed to his unbounded curiosity. Some of the entries were trivial, but others, notably those under the headings "Motion" and "Colors," were lengthy and the genesis of later major studies.

After about a year at Cambridge, Newton entered, almost for the first time, the field of mathematics, as usual following his own course of study. He soon traveled far enough into the world of seventeenth-century mathematical analysis to initiate his own explorations. These early studies would soon lead him to a geometrical demonstration of the fundamental theorem of calculus.

Beginning in the summer of 1665, life in Cambridge and in many other parts of England was shattered by the arrival of a ghastly visitor, the bubonic plague. For about two years the colleges were closed. Newton returned to Woolsthorpe, and took with him the many insights in mathematics and natural philosophy that had been rapidly unfolding in his mind.

Newton must have been the only person in England to recall the plague years 1665–66 with any degree of fondness. About fifty years later he wrote that "in those days I was in the prime of my age for invention & minded Mathematicks & Philosophy more then than at any time since." During these "miracle years," as they were later called, he began to think about the method of fluxions (his version of calculus), the theory of colors, and gravitation. Several times in his later years Newton told visitors that the idea of universal gravitation came to him when he saw an apple fall in the garden at Woolsthorpe; if gravity brought the apple down, he thought, why couldn't it reach higher, as high as the Moon?

These ideas were still fragmentary, but profound nevertheless. Later they would be built into the foundations of Newton's most important work. "The miracle," says Westfall, "lay in the incredible program of study undertaken in private and prosecuted alone by a young man who thereby assimilated the achievement of a century and placed himself at the forefront of European mathematics and science."

Genius of this magnitude demands, but does not always receive, recognition. Newton was providentially lucky. After graduation with a bachelor's degree, the only way he could remain at Cambridge and continue his studies was to be elected a fellow of Trinity College. Prospects were dim. Trinity had not elected fellows for three years, only nine places were to be filled, and there were many candidates. Newton was not helped by his previous subsizar status and unorthodox program of studies. But against all odds, he was included among the elected. Evidently he had a patron, probably Humphrey Babington, who was related to Clark, the apothecary in Grantham, and a senior fellow of Trinity.

The next year after election as a "minor" fellow, Newton was awarded the Master of Arts degree and elected a "major" fellow. Then in 1668, at age twenty-seven and still insignificant in the college, university, and scientific hierarchy, he was appointed Lucasian Professor of Mathematics. His patron for this surprising promotion was Isaac Barrow, who was retiring from the Lucasian chair and expecting a more influential appointment outside the university. Barrow had seen enough of Newton's work to recognize his brilliance.

Newton's Trinity fellowship had a requirement that brought him to another serious crisis. To keep his fellowship he regularly had to affirm his belief in the articles of the Anglican Church, and ultimately be ordained a clergyman. Newton met the requirement several times, but by 1675, when he could no longer escape the ordination rule, his theological views had taken a turn toward heterodoxy, even heresy. In the 1670s Newton immersed himself in theological studies that eventually led him to reject the doctrine of the Trinity. This was heresy, and if admitted, meant the ruination of his career. Although Newton kept his heretical views secret, ordination was no longer a possibility, and for a time, his Trinity fellowship and future at Cambridge appeared doomed.

But providence intervened, once again in the form of Isaac Barrow. Since leaving Cambridge, Barrow had served as royal chaplain. He had the connections at Court to arrange a royal dispensation exempting the Lucasian Professor from the ordination requirement, and another chapter in Newton's life had a happy ending.

Critics

Newton could not stand criticism, and he had many critics. The most prominent and influential of these were Robert Hooke in England, and Christiaan Huygens and Gottfried Leibniz on the Continent.

Hooke has never been popular with Newton partisans. One of his contemporaries described him as "the most ill-natured, conceited man in the world, hated and despised by most of the Royal Society, pretending to have all other inventions when once discovered by their authors." There is a grain of truth in this concerning Hooke's character, but he deserves better. In science he made contributions to optics, mechanics, and even geology. His skill as an inventor was renowned, and he was a surveyor and an architect. In personality, Hooke and Newton were polar opposites. Hooke was a gregarious extrovert, while Newton, at least during his most creative years, was a secretive introvert. Hooke did not hesitate to rush into print any ideas that seemed plausible. Newton shaped his concepts by thinking about them for years, or even decades. Neither man could bear to acknowledge any influence from the other. When their interests overlapped, bitter confrontations were inevitable.

Among seventeenth-century physicists, Huygens was most nearly Newton's equal. He made important contributions in mathematics. He invented the pendulum clock and developed the use of springs as clock regulators. He studied telescopes and microscopes and introduced improvements in their design. His studies in mechanics touched on statics, hydrostatics, elastic collisions, projectile motion, pendulum theory, gravity theory, and an implicit force concept, including the concept of centrifugal force. He pictured light as a train of wave fronts transmitted through a medium consisting of elastic particles. In matters relating to physics, this intellectual menu is strikingly similar to that of Newton. Yet Huygens's influence beyond his own century was slight, while Newton's was enormous. One of Huygens's limitations was that he worked alone and had few disciples. Also, like Newton, he often hesitated to publish, and when the work finally saw print others had covered the same ground. Most important, however, was his philosophical bias. He followed René Descartes in the belief that natural phenomena must have mechanistic explanations. He rejected Newton's theory of universal gravitation, calling it "absurd," because it was no more than mathematics and proposed no mechanisms.

Leibniz, the second of Newton's principal critics on the Continent, is remembered more as a mathematician than as a physicist. Like that of Huygens, his physics was limited by a mechanistic philosophy. In mathematics he made two major contributions, an independent (after Newton's) invention of calculus, and an early development of the principles of symbolic logic. One manifestation of Leibniz's calculus can be seen today in countless mathematics and physics textbooks: his notation. The basic operations of calculus are differentiation and integration, accomplished with derivatives and integrals. The Leibniz symbols for derivatives (e.g., $\frac{dy}{dx}$) and integrals (e.g., $\int ydx$) have been in constant use for more than three hundred years. Unlike many of his scientific colleagues, Leibniz never held an academic post. He was everything but an academic, a lawyer, statesman, diplomat, and professional genealogist, with assignments such as arranging peace negotiations, tracing royal pedigrees, and mapping legal reforms. Leibniz and Newton later engaged in a sordid clash over who invented calculus first.

Calculus Lessons

The natural world is in continuous, never-ending flux. The aim of calculus is to describe this continuous change mathematically. As modern physicists see it, the methods of calculus solve two related problems. Given an equation that expresses a continuous change, what is the equation for the rate of the change? And, conversely, given the equation for the rate of change, what is the equation for the change? Newton approached calculus this way, but often with geometrical arguments that are frustratingly difficult for those with little geometry. I will avoid Newton's complicated constructions and present here for future reference a few rudimentary calculus lessons more in the modern style.

Suppose you want to describe the motion of a ball falling freely from the Tower in Pisa. Here the continuous change of interest is the trajectory of the ball, expressed in the equation

$$s = \frac{gt^2}{2} \tag{1}$$

in which t represents time, s the ball's distance from the top of the tower, and g a constant we will interpret later as the gravitational acceleration. One of the problems of calculus is to begin with equation (1) and calculate the ball's rate of fall at every instant.

This calculation is easily expressed in Leibniz symbols. Imagine that the ball is located a distance s from the top of the tower at time t, and that an instant later, at time $t + dt$, it is located at $s + ds$; the two intervals dt and ds, called "differentials" in the terminology of calculus, are comparatively very small. We have equation (1) for time t at the beginning of the instant. Now write the equation for time $t + dt$ at the end of the instant, with the ball at $s + ds$,

$$\begin{aligned} s + ds &= \frac{g(t + dt)^2}{2} \\ &= \frac{g}{2}[t^2 + 2tdt + (dt)^2] \\ &= \frac{gt^2}{2} + gtdt + \frac{g}{2}(dt)^2. \end{aligned} \tag{2}$$

Notice the term s on the left side of the last equation and the term $\frac{gt^2}{2}$ the right. According to equation (1), these terms are equal, so they can be canceled from the last equation, leaving

$$\mathrm{d}s = gtdt + \frac{g}{2}(dt)^2. \tag{3}$$

In the realm where calculus operates, the time interval dt is very small, and $(dt)^2$ is much smaller than that. (Squares of small numbers are much smaller numbers; for example, compare 0.001 with $(0.001)^2 = 0.000001$.) Thus the term containing $(dt)^2$ in equation (3) is much smaller than the term containing dt, in fact, so small it can be neglected, and equation (3) finally reduces to

$$ds = gtdt. \tag{4}$$

Dividing by the dt factor on both sides of this equation, we have finally

$$\frac{ds}{dt} = gt. \tag{5}$$

(As any mathematician will volunteer, this is far from a rigorous account of the workings of calculus.)

This result has a simple physical meaning. It calculates the instantaneous speed of the ball at time t. Recall that speed is always calculated by dividing a distance interval by a time interval. (If, for example, the ball falls 10 meters at constant speed for 2 seconds, its speed is $\frac{10}{2} = 5$ meters per second.) In equation (5), the instantaneous distance and time intervals ds and dt are divided to calculate the instantaneous speed $\frac{ds}{dt}$.

The ratio $\frac{ds}{dt}$ in equation (5) is called a "derivative," and the equation, like any other containing a derivative, is called a "differential equation." In mathematical physics, differential equations are ubiquitous. Most of the theories mentioned in this book rely on fundamental differential equations. One of the rules of theoretical physics is that (with a few exceptions) its laws are most concisely stated in the common language of differential equations.

The example has taken us from equation (1) for a continuous change to equation (5) for the rate of the change at any instant. Calculus also supplies the means to reverse this argument and derive equation (1) from equation (5). The first step is to return to equation (4) and note that the equation calculates only one differential step, ds, in the trajectory of the ball. To derive equation (1) we must add all of these steps to obtain the full trajectory. This summation is an "integration" operation and in the Leibniz notation it is represented by the elongated-S symbol $\int$. For integration of equation (4) we write

$$\int ds = \int gtdt. \tag{6}$$

We know that this must be equivalent to equation (1), so we infer that the rules for evaluating the two "integrals" in equation (6) are

$$\int ds = s, \tag{7}$$

and

$$\int gtdt = \frac{gt^2}{2}. \tag{8}$$

Integrals and integration are just as fundamental in theoretical physics as differential equations. Theoreticians usually compose their theories by first writing differential equations, but those equations are likely to be inadequate for the essential further task of comparing the predictions of the theory with experimental and other observations. For that, integrated equations are often a necessity. The great misfortune is that some otherwise innocent-looking differential equations are extremely difficult to integrate. In some important cases (including one Newton struggled with for many years, the integration of the equations of motion for the combined system comprising Earth, the Moon, and the Sun), the equations cannot be handled at all without approximations.

A glance at a calculus textbook will reveal the differentiation rule used to arrive at equation (5), the integration rules (7) and (8), and dozens of others. As its name implies, calculus is a scheme for calculating, in particular for calculations involving derivatives and differential equations. The scheme is organized around the differentiation and integration rules.

Calculus provides a perfect mathematical context for the concepts of mechanics. In the example, the derivative $\frac{ds}{dt}$ calculates a speed. Any speed v is calculated the same way,

$$v = \frac{ds}{dt}. \tag{9}$$

If the speed changes with time—if there is an acceleration—that can be expressed as the rate of change in v, as the derivative $\frac{dv}{dt}$. So the acceleration differential equation is

$$a = \frac{dv}{dt}, \tag{10}$$

in which a represents acceleration. The freely falling ball accelerates, that is, its speed increases with time, as equation (5) combined with equation (9), which is written

$$v = gt, \tag{11}$$

shows. The constant factor g is the acceleration of free fall, that is, the gravitational acceleration.

This discussion has used the Leibniz notation throughout. Newton's calculus notation was similar but less convenient. He emphasized rates of change with time, called them "fluxions," and represented them with an overhead dot notation. For example, in Newton's notation, equation (5) becomes

$$\dot{s} = gt,$$

in which $\dot{s}$, Newton's symbol for $\frac{ds}{dt}$, is the distance fluxion, and equation (10) is

$$a = \dot{v},$$

with $\dot{v}$ representing $\frac{dv}{dt}$, the speed fluxion.

Optics

The work that first brought Newton to the attention of the scientific community was not a theoretical or even a mathematical effort; it was a prodigious technical achievement. In 1668, shortly before his appointment as Lucasian Professor, Newton designed and constructed a "reflecting" telescope. In previous telescopes, beginning with the Dutch invention and Galileo's improvement, light was refracted and focused by lenses. Newton's telescope *reflected* and focused light with a concave mirror. Refracting telescopes had limited resolution and to achieve high magnification had to be inconveniently long. (Some refracting telescopes at the time were a hundred feet long, and a thousand-footer was planned.) Newton's design was a considerable improvement on both counts.

Newton's telescope project was even more impressive than that of Galileo. With no assistance (Galileo employed a talented instrument maker), Newton cast and ground the mirror, using a copper alloy he had prepared, polished the mirror, and built the tube, the mount, and the fittings. The finished product was just six inches in length and had a magnification of forty, equivalent to a refracting telescope six feet long.

Newton was not the first to describe a reflecting telescope. James Gregory, professor of mathematics at St. Andrews University in Scotland, had earlier published a design similar to Newton's, but could not find craftsmen skilled enough to construct it.

No less than Galileo's, Newton's telescope was vastly admired. In 1671, Barrow demonstrated it to the London gathering of prominent natural philosophers known as the Royal Society. The secretary of the society, Henry Oldenburg, wrote to Newton that his telescope had been "examined here by some of the most eminent in optical science and practice, and applauded by them." Newton was promptly elected a fellow of the Royal Society.

Before the reflecting telescope, Newton had made other major contributions in the field of optics. In the mid-1660s he had conceived a theory that held that ordinary white light was a mixture of pure colors ranging from red, through orange, yellow, green, and blue, to violet, the rainbow of colors displayed by a prism when it receives a beam of white light. In Newton's view, the prism separated the pure components by refracting each to a different extent. This was a contradiction of the prevailing theory, advocated by Hooke, among others, that light in the purest form is white, and colors are modifications of the pristine white light.

Newton demonstrated the premises of his theory in an experiment employing two prisms. The first prism separated sunlight into the usual red-through-violet components, and all of these colors but one were blocked in the beam received by the second prism. The crucial observation was that the second prism caused no further modification of the light. "The purely red rays refracted by the second prism made no other colours but red," Newton observed in 1666, "& the purely blue no other colours but blue ones." Red and blue, and other colors produced by the prism, were the pure colors, not the white.

Soon after his sensational success with the reflecting telescope in 1671, Newton sent a paper to Oldenburg expounding this theory. The paper was read at a meeting of the Royal Society, to an enthusiastically favorable response. Newton was then still unknown as a scientist, so Oldenburg innocently took the additional step of asking Robert Hooke, whose manifold interests included optics, to comment on Newton's theory. Hooke gave the innovative and complicated paper about three hours of his time, and told Oldenburg that Newton's arguments were not convincing.

This response touched off the first of Newton's polemical battles with his critics. His first reply was restrained; it prompted Hooke to give the paper in question more scrutiny, and to focus on Newton's hypothesis that light is particle-like. (Hooke had found an inconsistency here; Newton claimed that he did not rely on hypotheses.) Newton was silent for awhile, and Hooke, never silent, claimed that he had built a reflecting telescope before Newton. Next, Huygens and a Jesuit priest, Gaston Pardies, entered the controversy. Apparently in support of Newton, Huygens wrote, "The theory of Mr. Newton concerning light and colors appears highly ingenious to me." In a communication to the *Philosophical Transactions* of the Royal Society, Pardies questioned Newton's prism experiment, and Newton's reply, which also appeared in the *Transactions*, was condescending. Hooke complained to Oldenburg that Newton was demeaning the debate, and Oldenburg wrote a cautionary letter to Newton. By this time, Newton was aroused enough to refute all of Hooke's objections in a lengthy letter to the Royal Society, later published in the *Transactions*. This did not quite close the dispute; in a final episode, Huygens reentered the debate with criticisms similar to those offered by Hooke.

In too many ways, this stalemate between Newton and his critics was petty, but it turned finally on an important point. Newton's argument relied crucially on experimental evidence; Hooke and Huygens would not grant the weight of that evidence. This was just the lesson Galileo had hoped to teach earlier in the century. Now it was Newton's turn.

Alchemy and Heresy

In his nineteenth-century biography of Newton, David Brewster surprised his readers with an astonishing discovery. He revealed for the first time that Newton's papers included a vast collection of books, manuscripts, laboratory notebooks, recipes, and copied material on alchemy. How could "a mind of such power . . . stoop to be even the copyist of the most contemptible alchemical poetry," Brewster asked. Beyond that he had little more to say about Newton the alchemist.

By the time Brewster wrote his biography, alchemy was a dead and unlamented endeavor, and the modern discipline of chemistry was moving forward at a rapid pace. In Newton's century the rift between alchemy and chemistry was just beginning to open, and in the previous century alchemy *was* chemistry.

Alchemists, like today's chemists, studied conversions of substances into other substances, and prescribed the rules and recipes that governed the changes. The ultimate conversion for the alchemists was the transmutation of metals, including the infamous transmutation of lead into gold. The theory of transmutation had many variations and refinements, but a fundamental part of the doctrine was the belief that metals are compounded of mercury and sulfur—not ordinary mercury and sulfur but principles extracted from them, a "spirit of sulfur" and a "philosophic mercury." The alchemist's goal was to extract these principles from impure natural mercury and sulfur; once in hand, the pure forms could be combined to achieve the desired transmutations. In the seventeenth century, this program was still plausible enough to attract practitioners, and the practitioners patrons, including kings.

The alchemical literature was formidable. There were hundreds of books (Newton had 138 of them in his library), and they were full of the bizarre terminology and cryptic instructions alchemists devised to protect their work from competitors. But Newton was convinced that with thorough and discriminating study, coupled with experimentation, he could mine a vein of reliable observations beneath all the pretense and subterfuge. So, in about 1669, he plunged into the world of alchemy, immediately enjoying the challenges of systematizing the chaotic alchemical literature and mastering the laboratory skills demanded by the alchemist's fussy recipes.

Newton's passion for alchemy lasted for almost thiry years. He accumulated more than a million words of manuscript material. An assistant, Humphrey Newton (no relation), reported that in the laboratory the alchemical experiments gave Newton "a great deal of satisfaction & Delight. . . . The Fire [in the laboratory furnaces] scarcely going out either Night or Day. . . . His Pains, his Dilligence at those sett times, made me think, he aim'd at something beyond y^{e} Reach of humane Art & Industry."

What did Newton learn during his years in company with the alchemists? His transmutation experiments did not succeed, but he did come to appreciate a fundamental lesson still taught by modern chemistry and physical chemistry: that the particles of chemical substances are affected by the forces of attraction and repulsion. He saw in some chemical phenomena a "principle of sociability" and in others "an endeavor to recede." This was, as Westfall writes, "arguably the most advanced product of seventeenth-century chemistry." It presaged the modern theory of "chemical affinities," which will be addressed in chapter 10.

For Newton, the attraction forces he saw in his crucibles were of a piece with the gravitational force. There is no evidence that he equated the two kinds of forces, but some commentators have speculated that his concept of universal gravitation was inspired, not by a Lincolnshire apple, but by the much more complicated lessons of alchemy.

During the 1670s, Newton had another subject for continual study and thought; he was concerned with biblical texts instead of scientific texts. He became convinced that the early Scriptures expressed the Unitarian belief that although Christ was to be worshipped, he was subordinate to God. Newton cited historical evidence that this text was corrupted in the fourth century by the introduction of the doctrine of the Trinity. Any form of anti-Trinitarianism was considered heresy in the seventeenth century. To save his fellowship at Cambridge, Newton kept his unorthodox beliefs secret, and, as noted, he was rescued by a special dispensation when he could no longer avoid the ordination requirement of the fellowship.

Halley's Question

In the fall of 1684, Edmond Halley, an accomplished astronomer, traveled to Cambridge with a question for Newton. Halley had concluded that the gravitational force between the Sun and the planets followed an inverse-square law—that is, the connection between this "centripetal force" (as Newton later called it) and the distance r between the centers of the planet and the Sun is

$$\text{centripetal force} \propto \frac{1}{r^2}.$$

(Read "proportional to" for the symbol $\propto$.) The force decreases by $\frac{1}{2}^2 = \frac{1}{4}$ if r doubles, by $\frac{1}{3}^2 = \frac{1}{9}$ if r triples, and so forth. Halley's visit and his question were later described by a Newton disciple, Abraham DeMoivre:

> In 1684 D^{r} Halley came to visit [Newton] at Cambridge, after they had some time together, the D^{r} asked him what he thought the curve would be that would be described by the Planets supposing the force of attraction towards the Sun to be reciprocal to the square of their distance from it. S^{r} Isaac replied immediately that it would be an [ellipse], the Doctor struck with joy & amazement asked him how he knew it, why saith he I have calculated it, whereupon D^{r} Halley asked him for his calculation without farther delay, S^{r} Isaac looked among his papers but could not find it, but he promised him to renew it, & then send it to him.

A few months later Halley received the promised paper, a short, but remarkable, treatise, with the title *De motu corporum in gyrum* (On the Motion of Bodies in Orbit). It not only answered Halley's question, but also sketched a new system of celestial mechanics, a theoretical basis for Kepler's three laws of planetary motion.

Kepler's Laws

Johannes Kepler belonged to Galileo's generation, although the two never met. In 1600, Kepler became an assistant to the great Danish astronomer Tycho Brahe,

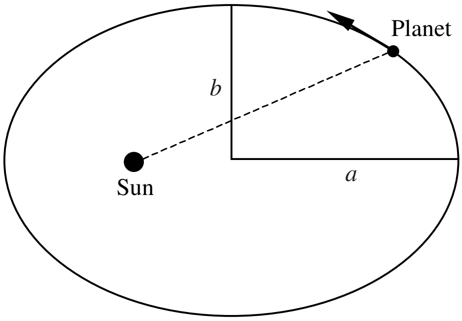


Figure 2.1. An elliptical planetary orbit. The orbit shown is exaggerated. Most planetary orbits are nearly circular.

and on Tycho's death, inherited both his job and his vast store of astronomical observations. From Tycho's data Kepler distilled three great empirical laws:

> *1. The Law of Orbits: The planets move in elliptical orbits, with the Sun situated at one focus.*

Figure 2.1 displays the geometry of a planetary ellipse. Note the dimensions a and b of the semimajor and semiminor axes, and the Sun located at one focus.

> *2. The Law of Equal Areas: A line joining any planet to the Sun sweeps out equal areas in equal times.*

Figure 2.2 illustrates this law, showing the radial lines joining a planet with the Sun, and areas swept out by the lines in equal times with the planet traveling different parts of its elliptical orbit. The two areas are equal, and the planet travels faster when it is closer to the Sun.

> *3. The Law of Periods: The square of the period of any planet about the Sun is proportional to the cube of the length of the semimajor axis.*

A planet's period is the time it requires to travel its entire orbit—365 days for Earth. Stated as a proportionality, with P representing the period and a the length of the semimajor axis, this law asserts that

$$P^2 \propto a^3.$$

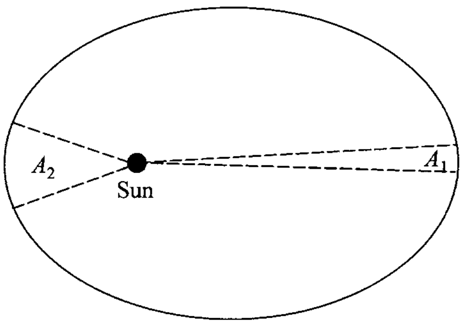


Figure 2.2. Kepler's law of equal areas. The area A_1 equals the area A_2.

Halley's Reward

"I keep [a] subject constantly before me," Newton once remarked, "and wait 'till the first dawnings open slowly, by little and little, into a full and clear light." Kepler's laws had been on Newton's mind since his student days. In "first dawnings" he had found connections between the inverse-square force law and Kepler's first and third laws, and now in *De motu* he was glimpsing in "a full and clear light" the entire theoretical edifice that supported Kepler's laws and other astronomical observations. Once more, Newton's work was "the passionate study of a man obsessed." His principal theme was the mathematical theory of universal gravitation.

First, he revised and expanded *De motu*, still focusing on celestial mechanics, and then aimed for a grander goal, a general dynamics, including terrestrial as well as celestial phenomena. This went well beyond *De motu*, even in title. For the final work, Newton chose the Latin title *Philosophiae naturalis principia mathematica* (Mathematical Principles of Natural Philosophy), usually shortened to the *Principia*.

When it finally emerged, the *Principia* comprised an introduction and three books. The introduction contains definitions and Newton's candidates for the fundamental laws of motion. From these foundations, book 1 constructs extensive and sophisticated mathematical equipment, and applies it to objects moving without resistance—for example, in a vacuum. Book 2 treats motion in resisting mediums—for example, in a liquid. And book 3 presents Newton's cosmology, his "system of the world."

In a sense, Halley deserves as much credit for bringing the *Principia* into the world as Newton does. His initial Cambridge visit reminded Newton of unfinished business in celestial mechanics and prompted the writing of *De motu*. When Halley saw *De motu* in November 1684, he recognized it for what it was, the beginning of a revolution in the science of mechanics. Without wasting any time, he returned to Cambridge with more encouragement. None was needed. Newton was now in full pursuit of the new dynamics. "From August 1684 until the spring of 1686," Westfall writes, "[Newton's] life [was] a virtual blank except for the *Principia*."

By April 1686, books 1 and 2 were completed, and Halley began a campaign for their publication by the Royal Society. Somehow (possibly with Halley exceeding his limited authority as clerk of the society), the members were persuaded at a general meeting and a resolution was passed, ordering "that Mr. Newton's *Philosophiae naturalis principia mathematica* be printed forthwith." Halley was placed in charge of the publication.

Halley now had the *Principia* on the road to publication, but it was to be a bumpy ride. First, Hooke made trouble. He believed that he had discovered the inverse-square law of gravitation and wanted recognition from Newton. The acknowledgment, if any, would appear in book 3, now nearing completion. Newton refused to recognize Hooke's priority, and threatened to suppress book 3. Halley had not yet seen book 3, but he sensed that without it the *Principia* would be a body without a head. "S^{r} I must now again beg you, not to let your resentment run so high, as to deprive us of your third book," he wrote to Newton. The beheading was averted, and Halley's diplomatic appeals may have been the decisive factor.

In addition to his editorial duties, Halley was also called upon to subsidize the publication of the *Principia*. The Royal Society was close to bankruptcy and unable even to pay Halley his clerk's salary of fifty pounds. In his youth, Halley had been wealthy, but by the 1680s he was supporting a family and his means were reduced. The *Principia* was a gamble, and it carried some heavy financial risks.

But finally, on July 5, 1687, Halley could write to Newton and announce that "I have at length brought your Book to an end." The first edition sold out quickly. Halley at least recovered his costs, and more important, he received the acknowledgment from Newton that he deserved: "In the publication of this work the most acute and universally learned Mr Edmund Halley not only assisted me in correcting the errors of the press and preparing the geometrical figures, but it was through his solicitations that it came to be published."

The *Principia*

What Halley coaxed from Newton is one of the greatest masterpieces in scientific literature. It is also one of the most inaccessible books ever written. Arguments in the *Principia* are presented formally as propositions with (sometimes sketchy) demonstrations. Some propositions are theorems and others are developed as illustrative calculations called "problems." The reader must meet the challenge of each proposition in sequence to grasp the full argument.

Modern readers of the *Principia* are also burdened by Newton's singular mathematical style. Propositions are stated and demonstrated in the language of geometry, usually with reference to a figure. (In about five hundred pages, the *Principia* has 340 figures, some of them extremely complicated.) To us this seems an anachronism. By the 1680s, when the *Principia* was under way, Newton had already developed his fluxional method of calculus. Why did he not use calculus to express his dynamics, as we do today?

Partly it was an aesthetic choice. Newton preferred the geometry of the "ancients," particularly Euclid and Appolonius, to the recently introduced algebra of Descartes, which played an essential role in fluxional equations. He found the geometrical method "much more elegant than that of Descartes . . . [who] attains the result by means of an algebraic calculus which, if one transcribed it in words (in accordance with the practice of the Ancients in their writings) is revealed to be boring and complicated to the point of provoking nausea, and not be understood."

There was another problem. Newton could not use the fluxion language he had invented twenty years earlier for the practical reason that he had never published the work (and would not publish it for still another twenty years). As the science historian François De Gandt explains, "[The] innovative character [of the *Principia*] was sure to excite controversy. To combine with this innovative character another novelty, this time mathematical, and to make unpublished procedures in mathematics the foundation for astonishing physical assertions, was to risk gaining nothing."

So Newton wrote the *Principia* in the ancient geometrical style, modified when necessary to represent continuous change. But he did not reach his audience. Only a few of Newton's contemporaries read the *Principia* with comprehension, and following generations chose to translate it into a more transparent, if less elegant, combination of algebra and the Newton-Leibniz calculus. The fate of the *Principia*, like that of some of the other masterpieces of scientific literature

(Clausius on thermodynamics, Maxwell on the electromagnetic field, Boltzmann on gas theory, Gibbs on thermodynamics, and Einstein on general relativity), was to be more admired than read.

The fearsome challenge of the *Principia* lies in its detailed arguments. In outline, free of the complicated geometry and the maddening figures, the work is much more accessible. It begins with definitions of two of the most basic concepts of mechanics:

> *Definition 1: The quantity of matter is the measure of the same arising from its density and bulk conjointly.*

> *Definition 2: The quantity of motion is the measure of the same, arising from the velocity and quantity of matter conjointly.*

By "quantity of matter" Newton means what we call "mass," "quantity of motion" in our terms is "momentum," "bulk" can be measured as a volume, and "density" is the mass per unit volume (lead is more dense than water, and water more dense than air). Translated into algebraic language, the two definitions read

$$m = \rho V, \tag{12}$$

and

$$p = mv, \tag{13}$$

in which mass is represented by m, density by ρ, volume by V, momentum by p, and velocity by v.

Following the definitions are Newton's axioms, his famous three laws of motion. The first is Galileo's law of inertia:

> *Law 1: Every body continues in its state of rest, or of uniform motion in a right [straight] line, unless it is compelled to change that state by forces impressed upon it.*

The second law of motion has more to say about the force concept:

> *Law 2: The change of motion is proportional to the motive force impressed; and is made in the direction of the right line in which the force is impressed.*

By "change of motion" Newton means the instantaneous rate of change in the momentum, equivalent to the time derivative $\dfrac{dp}{dt}$. In the modern convention, force is *defined* as this derivative, and the equation for calculating a force f is simply

$$f = \frac{dp}{dt}, \tag{14}$$

or, with the momentum p evaluated by equation (13),

$$f = \frac{d(mv)}{dt}. \tag{15}$$

The first two laws convey simple physical messages. Imagine that your car is coasting on a flat road with the engine turned off. If the car meets no resistance (for example, in the form of frictional effects), Newton's first law tells us that the car will continue coasting with its original momentum and direction forever. With the engine turned on, and your foot on the accelerator, the car is driven by the engine's force, and Newton's second law asserts that the momentum increases at a rate ($= \frac{dp}{dt}$) equal to the force. In other words: increase the force by depressing the accelerator and the car's momentum increases.

Newton's third law asserts a necessary constraint on forces operating mutually between two bodies:

> *Law 3: To every action there is always opposed an equal reaction: or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.*

Newton's homely example reminds us, "If you press on a stone with your finger, the finger is also pressed by the stone." If this were not the case, the stone would be soft and not stonelike.

Building from this simple, comprehensible beginning, Newton takes us on a grand tour of terrestrial and celestial dynamics. In book 1 he assumes an inverse-square centripetal force and derives Kepler's three laws. Along the way (in proposition 41), a broad concept that we now recognize as conservation of mechanical energy emerges, although Newton does not use the term "energy," and does not emphasize the conservation theme.

Book 1 describes the motion of bodies (for example, planets) moving without resistance. In book 2, Newton approaches the more complicated problem of motion in a resisting medium. This book was something of an afterthought, originally intended as part of book 1. It is more specialized than the other two books, and less important in Newton's grand scheme.

Book 3 brings the *Principia* to its climax. Here Newton builds his "system of the world," based on the three laws of motion, the mathematical methods developed earlier, mostly in book 1, and empirical raw material available in astronomical observations of the planets and their moons.

The first three propositions put the planets and their moons in elliptical orbits controlled by inverse-square centripetal forces, with the planets orbiting the Sun, and the moons their respective planets. These propositions define the centripetal forces mathematically but have nothing to say about their physical nature.

Proposition 4 takes that crucial step. It asserts "that the Moon gravitates towards the earth, and is always drawn from rectilinear [straight] motion, and held back in its orbit, by the force of gravity." By the "force of gravity" Newton means the force that causes a rock (or apple) to fall on Earth. The proposition tells us that the Moon is a rock and that it, too, responds to the force of gravity.

Newton's demonstration of proposition 4 is a marvel of simplicity. First, from the observed dimensions of the Moon's orbit he concludes that to stay in its orbit the Moon falls toward Earth 15.009 "Paris feet" (= 16.000 of our feet) every second. Then, drawing on accurate pendulum data observed by Huygens, he calculates that the number of feet the Moon (or anything else) would fall in one second on the surface of Earth is 15.10 Paris feet. The two results are close enough to each other to demonstrate the proposition.

Proposition 5 simply assumes that what is true for Earth and the Moon is true for Jupiter and Saturn and their moons, and for the Sun and its planets.

Finally, in the next two propositions Newton enunciates his universal law of gravitation. I will omit some subtleties and details here and go straight to the algebraic equation that is equivalent to Newton's inverse-square calculation of the gravitational attraction force F between two objects whose masses are m_1 and m_2,

$$F = G\frac{m_1 m_2}{r^2}, \tag{16}$$

where r is the distance separating the centers of the two objects, and G, called the "gravitational constant," is a universal constant. With a few exceptions, involving such bizarre objects as neutron stars and black holes, this equation applies to any two objects in the universe: planets, moons, comets, stars, and galaxies. The gravitational constant G is always given the same value; it is the hallmark of gravity theory. Later in our story, it will be joined by a few other universal constants, each with its own unique place in a major theory.

In the remaining propositions of book 3, Newton turns to more-detailed problems. He calculates the shape of Earth (the diameter at the equator is slightly larger than that at the poles), develops a theory of the tides, and shows how to use pendulum data to demonstrate variations in weight at different points on Earth. He also attempts to calculate the complexities of the Moon's orbit, but is not completely successful because his dynamics has an inescapable limitation: it easily treats the mutual interaction (gravitational or otherwise) of two bodies, but offers no exact solution to the problem of three or more bodies. The Moon's orbit is largely, but not entirely, determined by the Earth-Moon gravitational attraction. The full calculation is a "three-body" problem, including the slight effect of the Sun. In book 3, Newton develops an approximate method of calculation in which the Earth-Moon problem is first solved exactly and is then modified by including the "perturbing" effect of the Sun. The strategy is one of successive approximations. The calculations dictated by this "perturbation theory" are tedious, and Newton failed to carry them far enough to obtain good accuracy. He complained that the prospect of carrying the calculations to higher accuracy "made his head ache."

Publication of the *Principia* brought more attention to Newton than to his book. There were only a few reviews, mostly anonymous and superficial. As De Gandt writes, "Philosophers and humanists of this era and later generations had the feeling that great marvels were contained in these pages; they were told that Newton revealed truth, and they believed it. . . . But the *Principia* still remained a sealed book."

The *Opticks*

Newton as a young man skirmished with Hooke and others on the theory of colors and other aspects of optics. These polemics finally drove him into a silence of almost thirty years on the subject of optics, with the excuse that he did not want to be "engaged in Disputes about these Matters." What persuaded him to break the silence and publish more of his earlier work on optics, as well as some remarkable speculations, may have been the death of his chief adversary, Hooke, in 1703. In any case, Newton published his other masterpiece, the *Opticks*, in 1704.

The *Opticks* and the *Principia* are contrasting companion pieces. The two books have different personalities, and may indeed reflect Newton's changing persona. The *Principia* was written in the academic seclusion of Cambridge, and the *Opticks* in the social and political environment Newton entered after moving to London. The Opticks is a more accessible book than the *Principia*. It is written in English, rather than in Latin, and does not burden the reader with difficult mathematical arguments. Not surprisingly, Newton's successors frequently mentioned the *Opticks*, but rarely the *Principia*.

In the *Opticks*, Newton presents both the experimental foundations, and an attempt to lay the theoretical foundations, of the science of optics. He describes experiments that demonstrate the main physical properties of light rays: their reflection, "degree of refrangibility" (the extent to which they are refracted), "inflexion" (diffraction), and interference.

The term "interference" was not in Newton's vocabulary, but he describes interference effects in what are now called "Newton's rings." In the demonstration experiment, two slightly convex prisms are pressed together, with a thin layer of air between them; a striking pattern of colored concentric rings appears, surrounding points where the prisms touch.

Diffraction effects are demonstrated by admitting into a room a narrow beam of sunlight through a pinhole and observing that shadows cast by this light source on a screen have "Parallel Fringes or Bands of colour'd Light" at their edges.

To explain this catalogue of optical effects, Newton presents in the *Opticks* a theory based on the concept that light rays are the trajectories of small particles. As he puts it in one of the "queries" that conclude the *Opticks*: "Are not the Rays of Light very small Bodies emitted from shining Substances? For such Bodies will pass through Mediums in right Lines without bending into the Shadow, which is the Nature of the Rays of Light."

In another query, Newton speculates that particles of light are affected by optical forces of some kind: "Do not Bodies act upon Light at a distance, and by their action bend its Rays; and is not this action strongest at the least distance?"

With particles and forces as the basic ingredients, Newton constructs in the *Opticks* an optical mechanics, which he had already sketched at the end of book 1 of the *Principia*. He explains reflection and refraction by assuming that optical forces are different in different media, and diffraction by assuming that light rays passing near an object are more strongly affected by the forces than those more remote.

To explain the rings, Newton introduces his theory of "fits," based on the idea that light rays alternate between "Fits of easy Reflexion, and . . . Fits of easy Transmission." In this way, he gives the rays periodicity, that is, wavelike character. However, he does not abandon the particle point of view, and thus arrives at a complicated duality.

We now understand Newton's rings as an interference phenomenon, arising when two trains of waves meet each other. This theory was proposed by Thomas Young, one of the first to see the advantages of a simple wave theory of light, almost a century after the *Opticks* was published. By the 1830s, Young in England and Augustin Fresnel in France had demonstrated that all of the physical properties of light known at the time could be explained easily by a wave theory.

Newton's particle theory of light did not survive this blow. For seventy-five years the particles were forgotten, until 1905, when, to everyone's astonishment, Albert Einstein brought them back. (But we are getting about two centuries beyond Newton's story. I will postpone until later [chapter 19] an extended excursion into the strange world of light waves and particles.)

The queries that close the *Opticks* show us where Newton finally stood on two great physical concepts. In queries 17 through 24, he leaves us with a picture of the universal medium called the "ether," which transmits optical and gravitational forces, carries light rays, and transports heat. Query 18 asks, "Is not this medium exceedingly more rare and subtile than the Air, and exceedingly more elastick and active? And doth not it readily pervade all Bodies? And is it not (by its elastick force) expanded through all the Heavens?" The ether concept in one form or another appealed to theoreticians through the eighteenth and nineteenth centuries. It met its demise in 1905, that fateful year when Einstein not only resurrected particles of light but also showed that the ether concept was simply unnecessary.

In query 31, Newton closes the *Opticks* with speculations on atomism, which he sees (and so do we) as one of the grandest of the unifying concepts in physics. He places atoms in the realm of another grand concept, that of forces: "Have not the small particles of Bodies certain Powers, Virtues or Forces, by which they act at a distance, not only upon the Rays of Light for reflecting, refracting, and inflecting them [as particles], but also upon one another for producing a great Part of the Phaenomena of Nature?"

He extracts, from his intimate knowledge of chemistry, evidence for attraction and repulsion forces among particles of all kinds of chemical substances, metals, salts, acids, solvents, oils, and vapors. He argues that the particles are kinetic and indestructible: "All these things being considered, it seems probable to me, that God in the Beginning form'd Matter in solid, massy, hard, impenetrable, moveable Particles, of such Sizes and Figures, and in such Proportion to Space, as most conduced to the End for which he form'd them; even so very hard, as never to wear or break in pieces; no ordinary Power being able to divide what God himself made one in the First Creation."

London

There were two great divides in Newton's adult life: in the middle 1660s from the rural surroundings of Lincolnshire to the academic world of Cambridge, and thirty years later, when he was fifty-four, from the seclusion of Cambridge to the social and political existence of a well-placed civil servant in London. The move to London was probably inspired by a feeling that his rapidly growing fame deserved a more material reward than anything offered by the Lucasian Professorship. We can also surmise that he was guided by an awareness that his formidable talent for creative work in science was fading.

In March 1696, Newton left Cambridge, took up residence in London, and started a new career as warden of the Mint. The post was offered by Charles Montague, a former student and intimate friend who had recently become chancellor of the exchequer. Montague described the warden's office to Newton as a sinecure, noting that "it has not too much bus'nesse to require more attendance than you may spare." But that was not what Newton had in mind; it was not in his character to perform any task, large or small, superficially.

Newton did what he always did when confronted with a complicated problem: he studied it. He bought books on economics, commerce, and finance, asked searching questions, and wrote volumes of notes. It was fortunate for England that he did. The master of the Mint, under whom the warden served, was Thomas Neale, a speculator with more interest in improving his own fortune than in coping with a monumental assignment then facing the Mint. The English currency, and with it the Treasury, were in crisis. Two kinds of coins were in circulation, those produced by hammering a metal blank against a die, and those made by special machinery that gave each coin a milled edge. The hammered coins were easily counterfeited and clipped, and thus worth less than milled coins of the same denomination. Naturally, the hammered coins were used and the milled coins hoarded.

An escape from this threatening problem, general recoinage, had already been mandated before Newton's arrival at the Mint. He quickly took up the challenge of the recoinage, although it was not one of his direct responsibilities as warden. As Westfall comments, "[Newton] was a born administrator, and the Mint felt the benefit of his presence." By the end of 1696, less than a year after Newton went to the Mint, the crisis was under control. Montague did not hesitate to say later that, without Newton, the recoinage would have been impossible. In 1699 Neale died, and Newton, who was by then master in fact if not in name, succeeded him.

Newton's personality held many puzzles. One of the deepest was his attitude toward women. Apparently he never had a cordial relationship with his mother. Aside from a woman with whom he had a youthful infatuation and to whom he may have made a proposal of marriage, there was one other woman in Newton's life. She was Catherine Barton, the daughter of Newton's half-sister Hannah Smith. Her father, the Reverend Robert Barton, died in 1693, and sometime in the late 1690s she went to live with Newton in London. She was charming and beautiful and had many admirers, including Newton's patron, Charles Montague. She became Montague's mistress, no doubt with Newton's approval. The affair endured; when he died, Montague left her a generous income. She was also a friend of Jonathan Swift's, and he mentioned her frequently in his collection of letters, called *Journal to Stella*. Voltaire gossiped: "I thought . . . that Newton made his fortune by his merit. . . . No such thing. Isaac Newton had a very charming niece . . . who made a conquest of Minister Halifax [Montague]. Fluxions and gravitation would have been of no use without a pretty niece." After Montague's death, Barton married John Conduitt, a wealthy man who had made his fortune in service to the British army. The marriage placed him conveniently (and he was aptly named) for another career: he became an early Newton biographer.

Newton the administrator was a vital influence in the rescue of two institutions from the brink of disaster. In 1703, long after the recoinage crisis at the Mint, he was elected to the presidency of the Royal Society. Like the Mint when Newton arrived, the society was desperately in need of energetic leadership. Since the early 1690s its presidents had been aristocrats who were little more than figureheads. Newton quickly changed that image. He introduced the practice of demonstrations at the meetings in the major fields of science (mathematics, mechanics, astronomy and optics, biology, botany, and chemistry), found the society a new home, and installed Halley as secretary, followed by other disciples. He restored the authority of the society, but he also used that authority to get his way in two infamous disputes.

On April 16, 1705, Queen Anne knighted Newton at Trinity College, Cambridge. The ceremony appears to have been politically inspired by Montague (Newton was then standing for Parliament), rather than being a recognition of Newton's scientific achievements. Political or not, the honor was the climactic point for Newton during his London years.

More Disputes

Newton was contentious, and his most persistent opponent was the equally contentious Robert Hooke. The Newton story is not complete without two more accounts of Newton in rancorous dispute. The first of these was a battle over astronomical data. John Flamsteed, the first Astronomer Royal, had a series of observations of the Moon, which Newton believed he needed to verify and refine his lunar perturbation theory. Flamsteed reluctantly supplied the requested observations, but Newton found the data inaccurate, and Flamsteed took offense at his critical remarks.

About ten years later, Newton was still not satisfied with his lunar theory and still in need of Flamsteed's Moon data. He was now president of the Royal Society, and with his usual impatience, took advantage of his position and attempted to force Flamsteed to publish a catalogue of the astronomical data. Flamsteed resisted. Newton obtained the backing of Prince George, Queen Anne's husband, and Flamsteed grudgingly went ahead with the catalogue.

The scope of the project was not defined. Flamsteed wanted to include with his own catalogue those of previous astronomers from Ptolemy to Hevelius, but Newton wanted just the data needed for his own calculations. Flamsteed stalled for several years, Prince George died, and as president of the Royal Society, Newton assumed dictatorial control over the Astronomer Royal's observations. Some of the data were published as *Historia coelestis* (History of the Heavens) in 1712, with Halley as the editor. Neither the publication nor its editor was acceptable to Flamsteed.

Newton had won a battle but not the war. Flamsteed's political fortunes rose, and Newton's declined, with the deaths of Queen Anne in 1714 and Montague in 1715. Flamsteed acquired the remaining copies of *Historia coelestis*, separated Halley's contributions, and "made a sacrifice of them to Heavenly Truth" (meaning that he burned them). He then returned to the project he had planned before Newton's interference, and had nearly finished it when he died in 1719. The task was completed by two former assistants and published as *Historia coelestis britannica* in 1725. As for Newton, he never did get all the data he wanted, and was finally defeated by the sheer difficulty of precise lunar calculations.

Another man who crossed Newton's path and found himself in an epic dispute was Gottfried Leibniz. This time the controversy concerned one of the most precious of a scientist's intellectual possessions: priority. Newton and Leibniz both claimed to be the inventors of calculus.

There would have been no dispute if Newton had published a treatise composed in 1666 on his fluxion method. He did not publish that, or indeed any other mathematical work, for another forty years. After 1676, however, Leibniz was at least partially aware of Newton's work in mathematics. In that year, Newton wrote two letters to Leibniz, outlining his recent research in algebra and on fluxions. Leibniz developed the basic concepts of his calculus in 1675, and published a sketchy account restricted to differentiation in 1684 without mentioning Newton. For Newton, that publication and that omission were, as Westfall puts it, Leibniz's "original sin, which not even divine grace could justify."

During the 1680s and 1690s, Leibniz developed his calculus further to include integration, Newton composed (but did not publish) his *De quadratura* (*quadrature* was an early term for integration), and John Wallis published a brief account of fluxions in volume 2 of his *Algebra*. In 1699, a former Newton protégé, Nicholas Fatio de Duillier, published a technical treatise, *Lineae brevissimi* (Line of Quickest Descent), in which he claimed that Newton was the first inventor, and Leibniz the second inventor, of calculus. A year later, in a review of Fatio's *Lineae*, Leibniz countered that his 1684 book was evidence of priority.

The dispute was now ignited. It was fueled by another Newton disciple, John Keill, who, in effect, accused Leibniz of plagiarism. Leibniz complained to the secretary of the Royal Society, Hans Sloane, about Keill's "impertinent accusations." This gave Newton the opportunity as president of the society to appoint a committee to review the Keill and Leibniz claims. Not surprisingly, the committee found in Newton's favor, and the dispute escalated. Several attempts to bring Newton and Leibniz together did not succeed. Leibniz died in 1716; that cooled the debate, but did not extinguish it. Newtonians and Leibnizians confronted each other for at least five more years.

Nearer the Gods

Biographers and other commentators have never given us a consensus view of Newton's character. His contemporaries either saw him as all but divine or all but monstrous, and opinions depended a lot on whether the author was friend or foe. By the nineteenth century, hagiography had set in, and Newton as paragon emerged. In our time, the monster model seems to be returning.

On one assessment there should be no doubt: Newton was the greatest creative genius physics has ever seen. None of the other candidates for the superlative (Einstein, Maxwell, Boltzmann, Gibbs, and Feynman) has matched Newton's combined achievements as theoretician, experimentalist, *and* mathematician.

Newton was no exception to the rule that creative geniuses lead self-centered, eccentric lives. He was secretive, introverted, lacking a sense of humor, and prudish. He could not tolerate criticism, and could be mean and devious in the treatment of his critics. Throughout his life he was neurotic, and at least once succumbed to breakdown.

But he was no monster. He could be generous to colleagues, both junior and senior, and to destitute relatives. In disputes, he usually gave no worse than he received. He never married, but he was not a misogynist, as his fondness for Catherine Barton attests. He was reclusive in Cambridge, where he had little admiration for his fellow academics, but entertained well in the more stimulating intellectual environment of London.

If you were to become a time traveler and meet Newton on a trip back to the seventeenth century, you might find him something like the performer who first exasperates everyone in sight and then goes on stage and sings like an angel. The singing is extravagantly admired and the obnoxious behavior forgiven. Halley, who was as familiar as anyone with Newton's behavior, wrote in an ode to Newton prefacing the *Principia* that "nearer the gods no mortal can approach." Albert Einstein, no doubt equal in stature to Newton as a theoretician (and no paragon), left this appreciation of Newton in a foreword to an edition of the *Opticks*:

> Fortunate Newton, happy childhood of science! He who has time and tranquility can by reading this book live again the wonderful events which the great Newton experienced in his young days. Nature to him was an open book, whose letters he could read without effort. The conceptions which he used to reduce the material of experience to order seemed to flow spontaneously from experience itself, from the beautiful experiments which he ranged in order like playthings and describes with an affectionate wealth of details. In one person he combined the experimenter, the theorist, the mechanic and, not least, the artist in exposition. He stands before us strong, certain, and alone: his joy in creation and his minute precision are evident in every word and in every figure.

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Thermodynamics

Historical Synopsis

Our history now turns from mechanics, the science of motion, to thermodynamics, the science of heat. The theory of heat did not emerge as a quantitative science until late in the eighteenth century, when heat was seen as a weightless fluid called "caloric." The fluid analogy was suggested by the apparent "flow" of heat from a high temperature to a low temperature. Eighteenth-century engineers knew that with cleverly designed machinery, this heat flow could be used in a "heat engine" to produce useful work output.

The basic premise of the caloric theory was that heat was "conserved," meaning that it was indestructible and uncreatable; that assumption served well the pioneers in heat theory, including Sadi Carnot, whose heat engine studies begin our story of thermodynamics. But the doctrine of heat conservation was attacked in the 1840s by Robert Mayer, James Joule, Hermann Helmholtz, and others. Their criticism doomed the caloric theory, but offered little guidance for construction of a new theory.

The task of building the rudiments of the new heat science, eventually called thermodynamics, fell to William Thomson and Rudolf Clausius in the 1850s. One of the basic ingredients of their theory was the concept that any system has an intrinsic property Thomson called "energy," which he believed was somehow connected with the random motion of the system's molecules. He could not refine this molecular interpretation because in the mid–nineteenth century the structure and behavior—and even the existence—of molecules were controversial. But he could see that the energy of a system—not the heat—was conserved, and he expressed this conclusion in a simple differential equation.

In modern thermodynamics, energy has an equal partner called "entropy." Clausius introduced the entropy concept, and supplied the name, but he was ambivalent about recognizing its fundamental importance. He showed in a second simple differential equation how entropy is connected with heat and temperature, and stated formally the law now known as the second law of thermodynamics: that in an isolated system, entropy increases to a maximum value. But he hesitated to go further. The dubious status of the molecular hypothesis was again a concern.