## 3.1 Aristotle on Motion

The idea that a force causes motion goes back to the fourth century B.C., when the Greeks were developing some of the ideas of science. ✓ **Aristotle, the foremost Greek scientist, studied motion and divided it into two types: *natural motion* and *violent motion.***

Natural motion on Earth was thought to be either straight up or straight down, such as a boulder falling toward the ground or a puff of smoke rising in the air. Objects would seek their natural resting places: boulders on the ground and smoke high in the air like the clouds. It was "natural" for heavy things to fall and for very light things to rise. Aristotle proclaimed circular motion was natural for the heavens, for he saw both circular motion and the heavens as being without beginning or end. Thus, the planets and stars moved in perfect circles around Earth. Since these motions were considered natural, they were not thought to be caused by forces.

Violent motion, on the other hand, was imposed motion. It was the result of forces that pushed or pulled. A cart moved because it was pulled by a horse; a tug-of-war was won by pulling on a rope; a ship was pushed by the force of the wind. The important thing about defining violent motion was that it had an external cause. Violent motion was imparted to objects. Objects in their natural resting places could not move by themselves; they had to be pushed or pulled.

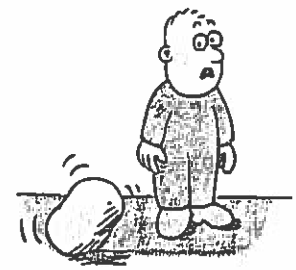


**FIGURE 3.1 ▲**
Boulders do not move without cause.

### Link to HISTORY

**Aristotle (384–322 B.C.)**

Aristotle was the most famous philosopher, scientist, and educator of ancient Greece. He was the son of a physician who personally served the king of Macedonia. At age 17, Aristotle entered the Academy of Plato, where he worked and studied for 20 years until Plato's death. He then became the tutor of young Alexander the Great. Eight years later, Aristotle formed his own school. His aim was to arrange existing knowledge in a system, just as Euclid had done earlier with geometry. Aristotle made careful observations, collected specimens, and gathered together and classified almost all existing knowledge of the physical world. His systematic approach became the method from which European science later arose. After his death, his voluminous notebooks were preserved in caves near his home and were later sold to the library at Alexandria. Scholarly activity came to a stop in most of Europe during the Dark Ages, and many of the works of Aristotle were forgotten and lost. Some of his texts, however, were reintroduced to Europe during the 1000s and 1100s and were translated into Latin. The Church, the dominant political and cultural force in Western Europe, at first prohibited the works of Aristotle. But soon thereafter the Church accepted them and incorporated them into Christian doctrine.

# 10

# Nicolaus Copernicus

## *and the Heliocentric Universe*

1473–1543

The notion of a stationary Earth at the center of the universe was supported by a mathematical system devised by the brilliant Greek astronomer Ptolemy. To his book, known to the Middle Ages as *Almagest*, we owe the description of the various constellations of stars such as the Big Dipper, still used today to describe the night sky. The Ptolemaic system was powerful and convincing for hundreds of years, and was, most important, the linchpin of a whole way of looking at the real world.* It was

*Ptolemy's brilliance as an astronomer and great influence should not be doubted. Only lack of space prevents his inclusion in *The Scientific 100*.

central to explanations of falling bodies and of the movements of stars and clouds, as well as to a whole theological interpretation of the place of human beings in the universe.

By the sixteenth century, however, with voyages of discovery bringing evidence of a more diverse world and with the authority of the Roman church faltering, Ptolemy's system began to crack. The posthumous publication in 1543 of *De revolutionibus orbium coelestium* (*On the Revolution of the Heavenly Bodies*), by Nicolaus Copernicus, eventually brought about its downfall. "The Earth," wrote Copernicus, "carrying the Moon's path, passes in a great orbit among the other Planets in an annual revolution around the Sun." Although not an accomplished fact for almost a century to come, the Copernican Revolution had begun.

Nicolaus Copernicus was born to prosperous circumstances on February 19, 1473, in Toruń, in the Kingdom of Poland. His father, Niklas Koppernign, was a merchant, and his mother, Barbara Watzenrode, was from an established and wealthy family. After the death of his father when he was ten years old, Nicolaus was raised by his maternal uncle, an academic and churchman who had become the bishop of Ermland in 1479. Nicolaus received an exemplary education. In 1491 he began attending the respected University of Cracow, then a center of natural philosophy. In 1496 Nicolaus moved to the University of Bologna, continuing his studies in Greek, mathematics, philosophy, and astronomy. About this time, he came under the influence of Domenico Maria da Novara, an astronomy professor who was an early critic of the Ptolemaic system, and on March 9, 1497, the two men witnessed together an eclipse of the moon. Copernicus studied at the University of Padua in 1501, then took a degree in law in 1503 from the University of Ferrara before returning to Padua for a course in medicine.

By 1506 Copernicus had completed his education—as a linguist, mathematician, and physician—and he returned to Poland, where he would remain until his death. He had been elected a canon in 1497 while he was a student abroad, and after several years as medical adviser to his uncle, upon the latter's death, he took up his duties as the canon of the Frauenburg Cathedral in newly established East Prussia. This was a church position with no religious duties, and Copernicus does not seem to have had any religious motivation in his life. He worked as a general administrator, judge, tax collector, and physician. In his spare time he was an astronomer, and in 1513 he constructed a tower to observe the stars.

Little is known about the genesis and development of Copernicus's thought, but he was by no means in a hurry to publish. He circulated a summary manuscript of his views on the cosmos as early as 1514 (it was not published until the nineteenth century), and he completed his great work in 1530. A decade later an admirer, George Joachim Rheticus, wrote a summary of the unpublished volume, entitled *Narratio prima*. When this book did not excite the animosity of the church—its implications were not immediately clear—Copernicus's objections may have been overcome. *De revolutionibus orbium coelestium* was published in Nuremburg in 1543, just as he died.

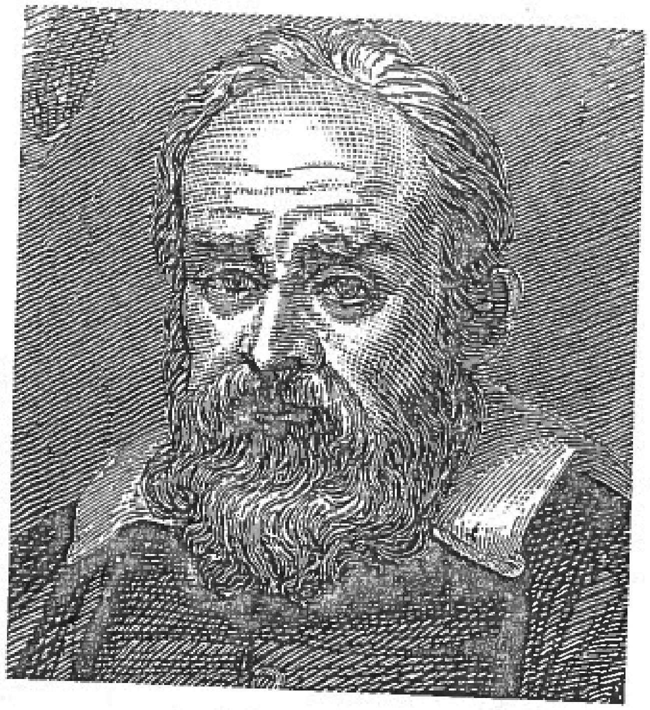
Copernicus strongly and persistently objects in *De revolutionibus* to Ptolemy's arguments for an immobile Earth. Reasoning on a physical basis with a prejudice toward harmony, Copernicus undermines the idea that Earth must be at the center of the universe. He points out, for example, that the stars do not always appear to be at the same distance from Earth. Efforts to explain such effects using epicycles—small circular orbits—were unsatisfactory and introduced awkward complications. For lack of physical theory, Copernicus ultimately developed a conception of the solar system which is a mixture of ancient and modern. He was aware of problems of acceleration and falling bodies, but had no solution. Without a modern conception of force, he retained the model of celestial spheres, not the notion of planets hurtling through space.

Eventually *De revolutionibus* found its way into the hands of learned men throughout Europe. Early readers of the book were at the very least fascinated by its mathematics, underscoring their growing dissatisfaction with the limitations of Ptolemaic astronomy. Religion did not object to the book, for during this era of the Reformation, the Catholic Church had bigger fish to fry. Not until 1616, and owing to Galileo's success, was Copernicus's book prohibited by the church.

The "Copernican Revolution" is an eminently useful term, although its actual content has been much discussed and disputed since it was first employed by Immanuel Kant two centuries ago. The term should be understood as referring to Copernicus's break with Ptolemaic astronomy and to his priority in developing a Sun-centered model. He did not accomplish it alone. It has long been understood that, as astronomer J. L. E. Dreyer wrote, "Copernicus did not produce what is nowadays meant by 'the Copernican system.'" And historian of science I. Bernard Cohen concludes, "If there was a revolution in astronomy, that revolution was Keplerian and Newtonian, and not in any simple or valid sense Copernican." This is not to gainsay Copernicus's influence but only to put it in the context of his real achievement. "One can easily argue that Copernicus was not the equal of Ptolemy or of Kepler in mathematics, although for his day he stood well above his contemporaries," argues Owen Gingerich. "Yet as a sensitive visionary who precipitated a scientific revolution, Copernicus stands as a cosmological genius with few equals."

Of the man himself, relatively little is known. His friend Rheticus's purported biography has been lost, as have most of his letters. According to legend, Copernicus received a copy of *De revolutionibus* on his deathbed. He had suffered a stroke, and could make no emendations but had the opportunity to handle the book before his death, which came on May 24, 1543. There remains the famous image—a man of honesty and devotion, high cheekbones and a penetrating gaze—which has come down to us in a handful of portraits. He did translate, from Greek into Latin, some eighty-five brief poems by the Byzantine poet Theophylactus Simocatta. Some of these *Epistles* are moral, others pastoral, and still others ribald. Fred Hoyle, the twentieth-century cosmologist, is grateful for the latter, for otherwise, he wrote, "I cannot hear Copernicus laugh."

7



# Galileo Galilei

## *and the New Science*

1564–1642

Galileo remains one of the most fascinating of early scientific figures, and his life and work have inspired a multitude of historians and critics. His achievements are many. He provided an early account of classical mechanics, and his descriptions of the night sky with a telescope laid the foundation of physical astronomy. But perhaps most significant, Galileo epitomized a new scientific outlook. By his rhetoric, supported by mathematical reasoning, and the force of his personality, Galileo helped to establish the Copernican model of the solar system as a revolution in science. Entirely aware of the philosophical implications of his new discoveries, he became a controversial and highly visible figure who was an embarrassment to the authority and dogma of the Catholic Church. Critics have long argued over the nature of his spirit of scientific inquiry; but Galileo's influence, in historical terms, is enormous.

Galileo Galilei was born in Pisa, Italy, on February 15, 1564, the son of Vincenzio Galilei, a musician and tradesman, and Giula Ammannati. (The first-name repetition of the surname was a Tuscan custom.) His family, which was not wealthy, moved to Florence when he was a child, and Galileo attended a Jesuit monastery school, but after becoming a novice at age fifteen, he was forced to withdraw by his father. In 1581 he entered the University of Pisa, planning to study medicine, but did not like it and acquired a reputation as disputatious. He soon transferred his interest to mathematics, and after leaving the university in 1585, without a degree, he returned to Florence to teach. In 1592, after the death of his father, he moved to Padua, where he continued teaching and invented, among other things, a military compass. He lived well; he acquired a mistress, Marina Gabba, and, to the distress of his aging mother, sired several illegitimate children.

Galileo's most significant early work, *De motu*, concerns the dynamics of motion and reflects his skepticism about the reigning—but crumbling—principles of scholastic science. According to Aristotle, an object in motion requires a constant mover; a ball, for example, is said to be propelled by air pushing behind it. This was a vulnerable point in Aristotelian physics, and it became an early locus of Galileo's interest. In all probability, Galileo was influenced by ballistics engineers, some of whom realized that a moving bullet appears to be pulled down to earth. Galileo recognized the importance of such observations. Experimenting on his own with a ball rolling off a table, he discovered a general law. Projectiles make a curved path as they fall. And, as a mathematician profoundly influenced by ARCHIMEDES [100], he summarized this discovery in a simple mathematical formula, described first in a letter dated 1604. (Mistakes in Galileo's calculations have given rise to considerable speculation among philosophers of science as to his intended line of reasoning.)

A new and important phase in Galileo's career began in 1609, when he learned of the invention of the telescope. He constructed his own model, which brought objects as much as one thousand times closer than they appeared to the naked eye. This he trained upon the moon. According to the old science of the cosmos, heavenly bodies were perfect in shape; Galileo found that Earth's satellite was pockmarked. He saw peaks and valleys and what he thought were seas. Looking out farther into the night sky, he discovered that the Milky Way consisted, so it seemed, of a multitude of stars—a far cry from the pristine night sky of Ptolemaic astronomy.

Indeed, the publication in 1610 of *Siderus nunicus (The Starry Messenger)* was a sensation; and historian J. R. Ravetz has called the slight book "perhaps the greatest classic ever of popular science, and also a masterpiece of subtle propaganda for the Copernican system." Learned men everywhere bought and read *The Starry Messenger*, and within five years there was even an edition in Chinese, translated by a Jesuit. Perhaps the most intriguing and remarkable of Galileo's discoveries was that four objects seemed to be circling the planet Jupiter, changing their position from night to night. To Galileo these were clearly satellites and resembled a Copernican scheme in miniature.

The success of *The Starry Messenger* put Galileo on the path to further discoveries, as well as on a collision course with the Catholic Church. However, he had first of all become a famous man, and his 1611 audience with the Pope was encouraging and friendly. Soon Galileo acquired a powerful patron in a former student, Cosimo II, the Grand Duke of Tuscany, who appointed Galileo his chief mathematician and philosopher. In 1612 Galileo's *Discourse on Floating Bodies* established hydrostatics, and the following year he published a series of letters in which he discussed his observations of sunspots. Here Galileo explicitly approved of COPERNICUS [10] and made an initial formulation of the principle of inertia. But by now, Galileo had aroused the wrath of church figures, and when in 1616 he visited Rome, he was admonished not to teach Copernicus's heliocentric views, against which a formal decree was issued. Galileo was not charged with heresy, however, and so may have taken a characteristically optimistic assessment of the situation. The historical record is a source of much debate.

When in 1623 Galileo published *The Assayer*, a polemic concerning the nature of comets, he dedicated it to Urban VIII, the new pope who (as Mafeo Barberini) had been an early supporter. Galileo hoped that the 1616 decree would be lifted, but his patron, Cosimo II, having died, Galileo was more vulnerable than before. He also received mixed messages from his old friend, who as pope was proving more the militarist than friend to science.* However, obtaining permission to discuss the systems of the world so long as he came to the right conclusion, Galileo wrote his *Dialogue Concerning the Two Chief World Systems*, which was published in 1632. In this work, a masterpiece of science, it is hard not to see Galileo's strong identification with his father, the author of a *Dialogue on Ancient and Modern Music*. Psychologically, this conceivably prevented Galileo from realizing the gravity of his undertaking.

The *Dialogue* was a great success when published in March 1633, but within six months the Inquisitor had stepped in. The *Dialogue* was banned, and Galileo was soon summoned once again to Rome, where he was technically imprisoned. Galileo's famous audience with Pope Urban VIII, and his grilling by the Inquisitor, have been the subject of much discussion over the years. The main issue was Galileo's disobedience of the 1616 admonitions. He has sometimes been taken to task for being less than courageous in face of these trials; in fact, he was a political prisoner, old and ill, and he was literally threatened with torture at a time when heretics were regularly, with cautionary fanfare, burned at the stake. In the end, the church prohibited and consigned the *Dialogues* to the flames, disgraced Galileo in a grand public spectacle, and refused to make him a martyr. He was imprisoned in fairly congenial circumstances.

It is a testament to Galileo's personal strength that the church's condemnation did not finish him by any means. His *Discourse on Two New Sciences*, published in Leyden in 1634, reprised his earlier experiments and discussed the properties of solids and the motion of falling bodies and projectiles. In 1637 he made his last scientific discovery: the wobbling of the moon. Although the *Dialogues* had been banned, it was soon known throughout Protestant Europe. Galileo was visited by the poet John Milton and the philosopher Thomas Hobbes, and his final letters, in which he professes faith in Aristotelian physics, may be read as ironic. At the end of his life Galileo was blind, apparently from cataracts, and he died on January 9, 1642.

Three and a half centuries after Galileo's death, Pope John

*Several years ago the scholar Pietro Redondi found documents at the Vatican suggesting that a Jesuit, Orazio Grassi, whom Galileo had ridiculed in *The Assayer*, was responsible for the trial which followed.

Paul II, who had served as Archbishop of Cracow and liked to refer to himself as the "Copernican Canon," conceded on behalf of the Catholic Church that Galileo had been unjustly treated. This admission, made in 1992, seems to have had a public relations angle. It was accorded a wry headline in the *New York Times*: "After 350 Years Vatican Says Galileo Was Right: It Moves." Three years earlier, in October 1989, the *Galileo*, a space probe, was launched from the space shuttle *Atlantis*. In 1995, the probe reached Jupiter, whose four moons Galileo had first viewed 385 years earlier.

Galileo was the great transitional figure in the history of science, and his work is formalized in that of ISAAC NEWTON [1]. However, the nature of Galileo's influence has been the subject of much scholarly debate over the past half century. In 1939 Alexandre Koyré described Galileo's great importance to science as primarily conceptual and philosophical and downplayed his use of experiment. This ignited considerable interest and led the scholar Stillman Drake to a more recent, painstaking reevaluation of Galileo's notes and manuscripts. Drake concluded "that a coherent depiction emerges of [Galileo] as a recognizably modern physical scientist" who made pioneering investigations on the nature of gravity. In either event, Galileo remains, together with JOHANNES KEPLER [9], the most significant figure in the scientific revolution before Newton.

# 1

# Isaac Newton

## *and the Newtonian Revolution*

1642–1727

Isaac Newton is the most influential figure in the history of Western science. He was considered a great intellectual hero in his lifetime, and adulation within the scientific community continues today, scarcely diminished after three hundred years. The reason is straightforward: When Newton came into it, the physical world was poorly understood, while by the time he died, on account of his works, it was known to be governed by mathematical laws of great accuracy. Newton did not initiate the scientific revolution, which was already well under way when he was born; his achievement was rather to give shape and provide the basic intellectual instruments of the modern science of physics. To

Newton are owed the three basic laws of motion and the law of gravity, by which all the physical phenomena on Earth, as in the heavens, become predictable, orderly, and in principle amenable to reason and manipulation by technology. Only in the twentieth century, when scientists began to deal with the smallest of magnitudes—the nature of the atom—did the validity of Newton's laws come into question.

Isaac Newton was born on December 25, 1642, in a small hamlet in Lincolnshire, England.* His yeoman father died before he was born, and his mother left him in the care of a grandmother when he was about three years old, to wed and live apart with Barnabas Smith, her second husband, a preacher and stepfather whom Newton detested. It is not surprising, given the experiences of his early childhood, that Newton as an adult evinced tendencies toward paranoia and violent rage. More interesting, perhaps, was his ability to countenance some of the aggression he felt: In a youthful catalogue of his sins Newton included "Threatening my father and mother Smith to burne them and the house over them." It should be recorded that Newton made his first important calculations—leading to the calculus—in the blank pages of his dead stepfather's commonplace book.

As a child Newton showed great curiosity and mechanical ability, and clearly he was not destined to become a farmer. In 1661 he matriculated at Trinity College, Cambridge. The university curriculum was largely weighted to Aristotelian philosophy; but within two years Newton had lost his appetite for *Nicomachean Ethics*. On his own initiative he began to read and make notes on the works of Francis Bacon, René Descartes, and other early scientific figures; and he conceived a passion for both mathematics and celestial phenomena. *Amicus Plato amicus Aristoteles magis amica veritas*, he wrote in his notebook. "Plato and Aristotle are my friends. But my best friend is Truth."

In 1664 Newton was selected to be a scholar at Trinity, a status which would have left him free to work on his own after taking his bachelor of arts degree the following year. But the

* This is Newton's birth date according to the Gregorian calendar introduced by papal decree in Europe in 1582 and used everywhere today. But in England, Newton's date of birth was recorded by the old-style Julian calendar as January 6, 1643.

Great Plague intervened. The university closed its doors in 1665, and Newton returned to stay with his mother, who was now widowed. There he remained two years, during which, as he described it later, "I was in the prime of my age for invention & minded Mathematicks & Philosophy more than at any time since." Indeed, building upon the geometry of Descartes, Newton invented an elementary calculus—that branch of mathematics which provides tools for computing the rate of change. Newton's "method of fluxions" became indispensable for solving problems raised anew, for the first time in hundreds of years, with the erosion of Aristotelian physics. During this early period Newton also conceived, at least in partial form, the universal law of gravitation and investigated the nature of light by experimenting with prisms. But although he composed his papers with great care—almost compulsively—he did not publish his findings for some years. The founder of modern science reworked his data constantly, for reasons which were surely emotional though not entirely clear, and long remained silent.

Returning to London in 1667, Newton was elected a fellow of Trinity College, University of Cambridge. In 1669, he took the position of Isaac Barrow—the first to recognize his genius—as the Lucasian Professor of Mathematics. He constructed the first reflecting telescope, which created a considerable stir, and which, in 1672, caused him to be elected to the Royal Society. However, when he offered an article, "New Theory About Light and Colours" to the Society, he was attacked by the eminent Robert Hooke. Wounded, Newton withdrew to continue his research in intellectual isolation.

In 1684 Newton received a visit from Edmond Halley, the great astronomer and mathematician, who discussed with him the then current problem of the motion of the planets. Hooke, for example, had proposed that planetary motion could be explained by the inverse square law, but he could not say why. The answer—that the planets move in elliptical orbits—Newton had effectively discovered years earlier by using his calculus. He returned to these questions now, publishing his *De motus corporum* in 1684, and over the next several years completed the more complete text, the *Philosophiae naturalis principia mathematica.* In this work, supported by a multitude of observations, Newton formulates the three laws of motion and the law of universal gravitation, to wit:

1. A body in motion moves with constant velocity unless acted upon by some force; a body at rest remains at rest unless acted upon by some force. This is the law of inertia.

2. An object's acceleration is in direct proportion to the force which acts upon it and inversely proportional to the object's mass. This may be expressed as the equation, *F*orce is equivalent to *m*ass multiplied by *a*cceleration, $F = ma$.

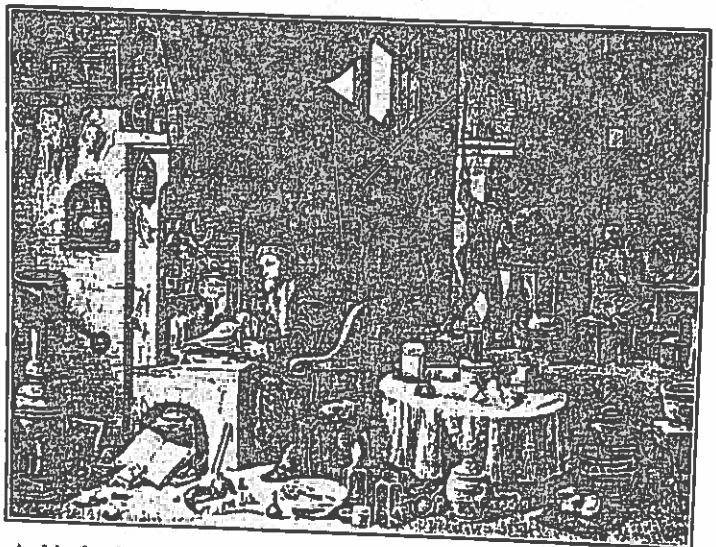
3. Every action evokes an equal and opposite reaction.

Newton's law of gravity states that *between any two bodies, the gravitational force is proportional to the product of their masses, and inversely proportional to the square of the distance between them.*

Published by Edmond Halley in 1687, the *Principia* was a great triumph which signaled the peak of Newton's career as a scientist, and the culmination of the scientific revolution.

Although Newton attained great prominence with the *Principia* and became a living symbol of the new science, his subsequent career was filled with contradictions. Beginning in 1689, after the English Revolution, he had a brief and undistinguished career in Parliament. In 1696 he was appointed warden of the Royal Mint, and three years later became master of the Mint, a position from which he was able to prosecute counterfeiters—as he did with great assiduity. He was elected president of the Royal Society in 1703 and held that office until his death, on March 31, 1727. In 1704, with the death of nemesis Robert Hooke, Newton published his *Opticks*. His authority was by then so great that his corpuscular theory of light was dominant for the next century in spite of certain flaws. He was the first scientific figure to be knighted, by Queen Anne, in 1705.

At his death, Newton left a huge trove of unpublished papers, which included over a million words on the esoteric and mystical study of alchemy. He had conducted studies over many years and in great depth, doing experiments by which he hoped, for example, to change base metal into philosopher's mercury. His alchemical researches, which share the diligence but not the careful rationalism of his physics, have long disturbed scholars. John Maynard Keynes, who purchased and studied the alchemical papers, ended by calling Newton a "magician" rather than a scientist—which is an interesting verdict coming from an economist. It is likely that the religious component in alchemy attracted Newton, as did its overarching goals; one of his



At his death Newton left a trove of alchemical research, at odds with his discoveries in physics, which has long baffled scientists and historians.

biographers, Gale Christianson, has suggested, for example, that Newton was aiming at a great synthetic understanding of the universe.

Newton's life is marked by a series of conflicts which can render him to modern eyes an unsympathetic figure. He was given to violent rages and unnecessarily rancorous disputes with contemporaries, such as Leibniz and Hooke. He seems to have had his strongest relationship with Nicolas Fatio de Duillier, a young admirer, the rupture of which likely contributed to a brief but wrenching mental breakdown. Newton never married—indeed, he was barred as a Cambridge fellow from doing so—and passed his adult life almost wholly in the company of men. He seldom laughed, although an anecdote that comes down to us is touching and revealing. When a friend said that he could not see how any use could come from studying Euclid, the Greek mathematician, Newton broke into merry laughter. For Erasmus Darwin, *Newton Explored in Nature's scenes the effect and cause, / And, charm'd, unravelled all her latent laws*. But more elegant is the couplet by Alexander Pope, written upon Newton's death and engraved in the room where he was born at Woolsthorpe Manor. *Nature and Nature's Laws lay hid in Night. / God said,* Let Newton be! *and all was* Light.