CHAPTER 5

Alexandria and After

Ancient Greek civilization developed in two phases. In the first, the *Hellenic,* city-states arose in Ionia and on the Greek peninsula. They were semi-prosperous, each supported by an agricultural hinterland (and, generally, by imported food), and they remained independent—there was no Greek king. Then, in the fourth century BCE, a second phase, the *Hellenistic,* took shape, marked successively by confederation, imperialism, and conquest. The result was a vast expansion of Greek culture and learning.

In Macedonia, the northern district of Greece, a local king, Philip II, gathered his forces, which included horse-mounted infantry and rock-throwing artillery, and began the unification of the Greek peninsula. When Philip was assassinated in 336 his son, Alexander, who became known to his contemporaries as "the Triumphant" and to us as "the Great," continued Philip's expansionist course and forged the most extensive empire in the ancient world. At its height it reached out from Old Greece and encompassed the great river valley civilization in Egypt, through the Mesopotamian heartland of the first civilizations on the flood plain of the Tigris and Euphrates Rivers, and on to the Indus River Valley in the east. The empire of Alexander the Great lasted only 11 years, from 334 when he defeated the Persians until his early death at the age of 33 in 323 BCE. After Alexander's death India returned to Indian control, and the empire collapsed into three kingdoms: Macedonia (including the Greek peninsula), Egypt, and the Seleucid Empire in Mesopotamia. (See inset, map 4.1 in previous chapter.) They were eleven years that changed the world.

The onset of the Hellenistic marks a break in the historical chronology of ancient science. Hellenic natural philosophy, with its unpatronized individualists, gave way to the more cosmopolitan world of the Hellenistic—the Golden Age of Greek science—and a new mode of organization and social support of research. Hellenistic science represents the historical melding or hybridization of the tradition of Hellenic natural philosophy with patterns of state-supported science that had originated in the eastern kingdoms. Kings and emperors had patronized a bureaucratic science that leaned toward useful applications; Hellenic science was the work of solitary thinkers who immersed themselves in abstract thought. Hellenistic science in the lands of the ancient Near East combined those disparate traditions. State support and patronage for scientific theory and abstract learning were novelties of Hellenistic culture and remained part of the historical pattern of science in all subsequent societies that inherited the Greek tradition.

The roots of the new scientific culture were planted in Egypt, now governed by a Greek ruling class which promptly established itself as an Egyptian dynasty—Ptolemaic Egypt. The first Greek king of Egypt, Ptolemaios Soter, began the tradition of royal patronage of science and learning, and it fell to his successor, Ptolemaios Philadelphus, to found the famous Museum at Alexandria, a new town built as a port on the Mediterranean shore of the Nile delta during Alexander's lifetime. With varying degrees of official support and patronage the Museum existed for 700 years—into the fifth century CE, an existence roughly as long as the world's oldest universities today. The distinctive character of Hellenistic and Greco-Roman science derives at least in part from this institutionalization of pure science and natural philosophy.

In essence, the Museum at Alexandria was a research institution—an ancient Institute for Advanced Study. Unlike its present namesake, the Museum did not display collections of objects (a function museums acquired only in the European Renaissance). It was, instead, a temple dedicated to the nine mythical Muses of culture—including Clio, the muse of history, and Urania, the muse of astronomy. There, subsidized members combining Greek and Oriental traditions, conducted their own research fully supported by state resources. In the royal precinct, the Ptolemies and their successors maintained splendid quarters for the Museum and its staff which included rooms, lecture halls, dissection studios, gardens, a zoo, an observatory, and possibly other facilities for research. The Ptolemies added a glorious library that soon contained 500,000 or more papyrus scrolls. Patronage always proved fickle in antiquity, depending on the largesse of individual kings and emperors, but at any one time the Museum harbored upwards of 100 scientists and literary scholars who received stipends from the state and meals from the Museum's kitchen while being allowed a Hellenic-style freedom of inquiry, excused even from the obligation to teach. No wonder the record indicates that stipendiaries were the targets of envious attacks as "rare birds" fed in gilded cages—such is the cultural ambiguity provoked by state support for pure learning. The later Roman emperors of Egypt kept up this extraordinary tradition of state support no less than their Hellenistic predecessors, making Alexandria the most significant center of science in the Hellenistic and Greco-Roman eras.

The motives of the Ptolemies and other Hellenistic and Greco-Roman patrons of science and learning are not clear. Doubtless they sought practical returns, and institutional pressure was at least indirectly brought to bear on the scientists at the Museum to bend their research toward useful applications. The fact that the Museum supported anatomical-medical research lends support to that conjecture. Similarly the zoo sheltered the war elephants of the king, the Library collected books on government and contemporary "political science," and academicians pursued geography and cartography. Applied military research may also have taken place at the Museum. Data suggest that Hellenistic scientists were somewhat more practically oriented than their earlier Hellenic counterparts. Beyond any immediate utility, however, it would seem that fame, glory, and prestige accruing to patrons were major motives for supporting the rare birds who roosted in the Museum. Whether the Ptolemies or their Roman successors got their money's worth depends on one's assessment of the relative values of the abstract and practical products of research.

The Hellenistic pattern of support for learning was not limited to Alexandria, and several cities in late antiquity came to boast of museums and libraries, including the library at Pergamum, a city that rivaled Alexandria as a center of state-supported science and scholarship. At Athens the institutional status of Plato's Academy and Aristotle's Lyceum is revealing in this regard. These schools, too, acquired a Hellenistic dimension. We saw that they began in the Hellenic era as informal, entirely private associations of masters and students devoted to the study of their founders' thought. They received legal status, notably as religious associations, but got no public support at the outset, remaining self-supporting as schools and communities of scholars. The formal institutional character of the Academy and the Lyceum became strengthened when, in the Alexandrian mode, the Roman emperors Antoninus Pius and Marcus Aurelius endowed imperial chairs in Athens and elsewhere in the second century CE. The Lyceum in Athens and the Museum at Alexandria also shared contacts and personnel. The Lyceum continued to be active at least until the end of the second century CE, and the Academy survived into the sixth century, nearly a thousand years after its founding. Still, the Lyceum and the Academy were primarily schools with teaching the key activity; research itself remained incidental, unlike the extraordinary case of the Alexandrian Museum where scholars received support for unfettered research.

Although literary and philological studies predominated at Alexandria, a historically unparalleled flourish of scientific activity also occurred there, especially during the first century of the Museum's existence, the third century BCE. A tradition of abstract, formal mathematics is the greatest and most enduring Alexandrian accomplishment. As exemplified by Euclid's geometry, Hellenistic mathematics was exceedingly formal and nonarithmetical, qualities that placed it far from the needs of artisans but squarely at the fountainhead of subsequent mathematical research. Euclid had probably studied at the Academy in Athens before he moved to Alexandria under the patronage of the Ptolemies. Apollonius of Perga (fl. 220–190 BCE) did most of his work there, too; he was known for his mastery of the conic sections (which found its first application in Johannes Kepler's astronomical theories 1,800 years later). To this tradition belongs Archimedes of Syracuse (287–212 BCE), probably the greatest mathematical genius of antiquity. Archimedes lived and died in Syracuse in Italy, but he traveled to Alexandria at one point and corresponded with the head of the Library, Eratosthenes of Cyrene (fl. 225 BCE). Eratosthenes, himself a multifaceted man of science, performed a famous observation and calculation to determine the circumference of the earth, and persons educated in the Greek tradition did not believe the earth to be flat; Eratosthenes also inaugurated notable work in geography and cartography. The latter fields of research continued in Alexandria down through the astronomer Ptolemy 400 years later. Innovative anatomical research also took place at the Museum, seen notably in the work of Herophilus of Chalcedon (fl. 270 BCE) and Erasistratus of Chios (fl. 260 BCE). Alexandrian anatomists evidently conducted human dissections and possibly vivisections as well. Other Alexandrian scientists undertook substantial research in astronomy, optics, harmonics, acoustics, and mechanics.

In astronomy, the Eudoxean model of geocentric spheres was challenged early in the Hellenistic period. The reader will recall the research tradition that stemmed from Plato's legendary injunction to "save the phenomena"—particularly the problem of the stations and retrogradations of the planets—and Eudoxus's geocentric solution in terms of his onion-skin universe and its rotating and counter-rotating spheres. But the model of nested homocentric spheres, even as refined by Aristotle, faced serious difficulties, notably in accurately reproducing the retrograde motions of planets. And the unequal lengths of the seasons, difficult to explain if the sun moves uniformly at a constant distance from a central earth, was another technical problem undermining the Eudoxean approach. Already in the fourth century—the century of Plato and Aristotle—Heraclides of Pontus (fl. 330 BCE) suggested that the apparent daily circling of the heavens could be accounted for by assuming that the heavens remained stationary as the earth spun on its axis once a day. The suggestion was generally considered implausible since it seemingly contradicted the direct sensory evidence that the earth is stationary.

Astronomical theory and cosmology posed questions that continued to excite the curiosity of many natural philosophers over subsequent centuries. One of those was Aristarchus of Samos (310–230 BCE), an expert astronomer and mathematician and, it seems, an associate of the Museum. According to Archimedes, Aristarchus espoused a heliocentric, or sun-centered, cosmology, not unlike the system proposed by Copernicus nearly 2,000 years later. He placed the sun at the center and attributed two motions to the earth: a daily rotation on its axis (to account for the apparent daily circuit of the heavens) and an annual revolution around the sun (to account for the apparent path of the sun around the zodiac).

Aristarchus's heliocentrism was known but overwhelmingly rejected in antiquity, not for some anti-intellectual bias but rather for its essential implausibility. The heliocentric theory, which in its essentials we hold today, faced so many scientific objections at the time that only a zealot would subscribe to it. If the earth whirled on its axis and raced around the sun, surely everything not nailed down would go flying off the earth or be left behind in a wake of debris, a conclusion contradicted by the sensible evidence of birds flying with equal ease in all directions and bodies projected directly upwards returning to where they began. In addition, the motion of the earth postulated by Aristarchus's heliocentrism plainly violated Aristotle's physics of natural motion. Earthy and watery things that make up the earth naturally tend to the center of the cosmos—to require the earth to spin like celestial matter or move otherwise through space is to ask it to undertake motions that Aristotle and all of science declared impossible. If the earth was displaced from the center, its parts would simply return and reorder themselves there. Rational scientists would never accept a theory that flew in the face of everyday observations and that violated long-held doctrines that formed the basis of ongoing, productive research. Today, we also become suspicious of people who propose ideas that violate the laws of physics.

A highly technical but scientifically more telling point also counted strongly against Aristarchus and his sun-centered theory, the problem of stellar parallax. To state the problem simply, if the earth orbits the sun, then the relative position of the stars ought to change over the course of six months as the earthbound observer viewed the heavens from widely different positions. But no such change was observed, at least not until the nineteenth century. (To observe parallax the reader might hold a finger in front of his or her nose and watch it "move" as the left and right eyes are alternately opened and closed.) Archimedes gives us Aristarchus's response to the difficulty: Aristarchus compared the size of the earth's orbit to a grain of sand, meaning that the diameter of the earth's orbit around the sun is so small in relation to the distance to the fixed stars that the change of stellar position would be too small to be observed. This was an ingenious answer for why stellar parallax cannot be observed (the same answer, incidentally, that Copernicus later gave), but Aristarchus then faced the further objection that the size of the universe had to be expanded to extraordinary, (then) unbelievable proportions in order for heliocentrism to hold. The scientific problems facing the heliocentric hypothesis were formidable, and ancient astronomers stood on strong ground in repudiating it. Religious objections also arose against setting the corrupt and changeable earth in the divine and incorruptible heavens. Not surprisingly, Aristarchus was threatened with charges of impiety.

The difficult problem of accounting for planetary motions resulted in alternatives to the astronomies of Eudoxus and Aristarchus. Apollonius of Perga, the Alexandrian scientist mentioned above in connection with the conic sections, helped build an alternative means of "saving the phenomena" and preserving geocentrism. He developed two powerful mathematical tools that astronomers used to model observed motion in the heavens: *epicycles* and *eccentrics*. The epicycle model had planets orbiting on small circles which in turn moved on larger circles; the eccentric is simply an off-centered circle. Both the retrograde motion of the planets and the variable lengths of the seasons could be easily and accurately modeled using epicycles. By assigning different sizes, speeds, and directions to these circles, Hellenistic astronomers developed increasingly accurate models for heavenly motion.

Ancient astronomy culminated in the work of Claudius Ptolemy in the second century CE. Ptolemy lived and worked under Roman governance in Alexandria. Building on his predecessors' use of epicycles and eccentrics Ptolemy composed a massive and highly technical manual of astronomy, the *Mathematical Syntaxis,* the celebrated *Almagest* (so named by later Muslim scholars). The Almagest is premised upon geocentrism and circular motion in the heavens and is extremely mathematical and geometrical in its approach. To his arsenal of epicycles and eccentrics, Ptolemy added a third tool, the so-called *equant* point, necessitated by the still-elusive harmony between planetary theory and observation. Viewed from the equant point an observer would see the planet move with uniform circular motion, while it was in fact moving at a changing rate with respect to the earth. Ptolemy's equant violated the spirit, if not the letter, of Plato's injunction to "save the phenomena" using uniform circular motion, but the objection was abstruse even to astronomers and in no way undermined commitments to geocentrism. The equant proved a handy tool, and Ptolemy deployed it and other improvisations to create elaborate, if wholly abstract, mathematical constructions, celestial "Ferris Wheels" whose stately turnings charted the eternal and unchanging heavens. In theory a "Ptolemaic" system with appropriate epicycles, eccentrics, and equants can be designed today to match the accuracy of *any* observed orbit. Ptolemy's *Almagest* was a major scientific achievement. For 1,500 years it remained the bible of every astronomer whose work derived from Hellenistic sources.

Ptolemy also contributed to a Greek tradition of geometrical optics, notably incorporating experimental data into his study of refraction—the bending of light in different media. And his work in geography and cartography similarly proved influential. But one should not put too modern a spin on Ptolemy. For him, mathematical science was a form of philosophy and essentially an ethical and spiritual enterprise. He believed the heavens to be divine and, indeed, animate. For Ptolemy, the movement of the heavens self-evidently affected the sublunary world (through the tides or the seasons, for example). Thus, although Ptolemy distinguished between astrology and astronomy, he recognized the legitimacy of astrology and the effort to predict the future. In fact, he wrote a large and influential book on astrology, the *Tetrabiblos,* and, not least of his many accomplishments, he may fairly be said to have been the greatest astrologer of antiquity.

An upsurge of alchemy matched the strength of contemporary astrology. What came to be the foundational texts of a semisecret tradition were compiled in Hellenistic Alexandria and elsewhere. The tradition is labeled "Hermetic" because these compilations were attributed to its mythical founder, Hermes Trismegistus, a legendary Egyptian priest thought to be living around the time of Moses. This body of mystical work contained esoteric and supposedly divinely inspired doctrines pertaining to the secret workings of the universe. Although the idea and practice that base metals can be transmuted into gold and silver doubtless involved some amount of fraud in antiquity, the roots of alchemy lay in demonstrated metallurgical practice, and alchemical science, so to speak, evolved out of Bronze and Iron Age technologies involving metals. Alchemy offered the promise of utility, and in that sense it represents another early practical science, especially to the extent that rulers patronized it. But for serious practitioners, the alchemical quest for elixirs of immortality or the philosopher's stone that would transmute metals always entailed a spiritual dimension, wherein the alchemist sought to purify himself as much as he hoped to purify base metals. Ancient and medieval alchemy should not be thought of as pseudochemistry. Rather, alchemy needs to be understood on its own as a technically based practical science that combined substantial mystical and spiritual elements.

The impact of alchemy was small, and on the whole Hellenistic science at Alexandria and elsewhere in the ancient world was not applied to technology or, in general, pursued for utilitarian ends. Natural philosophy remained largely insular, as it had been previously in the Hellenic. It remained isolated, not in any direct way connected or applied to the predominant practical problems of the age. In addition, the ideology stemming from Plato and the pre-Socratics that held manual labor in contempt and that repudiated any practical or economic utility to science continued in the Hellenistic. Ideology thus reinforced the existing separation of *theoria* and *praxis.*

Mechanics itself, however, was subject to scientific analysis by Hellenistic scientists in theoretical treatises on mechanics and the mechanical arts. Archimedes, above all, mastered the mechanical principles of the simple machines: the lever, wedge, screw, pulley, and windlass; and in analyzing the balance (including the hydrostatic balance), the ancients articulated a theoretical and mathematical science of weight. The prac-

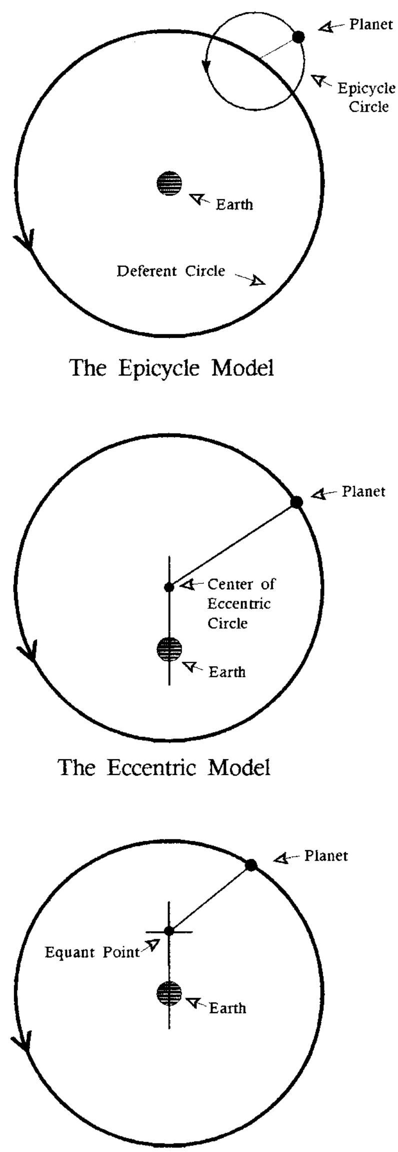


Fig. 5.1. Ptolemy's astronomical devices. To reconcile observed planetary positions with the doctrine of uniform circular motion Ptolemy employed epicycles, eccentric circles, and equant points. The epicycle model involves placing circles on circles; eccentrics are off-centered circles; the equant point is an imaginary point in space from which uniform circular motion is measured.

tical possibilities of this mechanical tradition are evident in the work of Ctesibius of Alexandria (fl. 270 BCE), Philo of Byzantium (fl. 200 BCE), and Hero of Alexandria (fl. 60 BCE). Based on their knowledge of weight and pneumatics, these men designed ingenious mechanical devices—in the category of "wondrous machines" that could automatically open temple doors or pour libations, but whose purpose was to provoke awe and wonder, and not to contribute to economic progress. Hero, for example, contrived to spin a ball using fire and steam, but no one in antiquity conceived or followed up with a practical steam engine. In a word, the study of mechanics in Alexandria was, like its kindred sciences, almost completely detached from the wider world of technology in antiquity.

But not completely. The Archimedean screw, for example, was a machine that lifted water; it was invented in the third century BCE purportedly by Archimedes, and it derived from this tradition of scientific mechanics. Archimedes, who died in 212 BCE during the defense of his native Syracuse against the Romans, became legendary for his technological wizardry with siege engines and war machinery. His published work remained abstract and philosophical, but even discounting as legend much that is credited to him, Archimedes probably did apply himself to engineering technology and practical achievement. He supposedly used his knowledge of mechanics in wartime, and in this capacity he acted as an ancient engineer (*architecton*), one of whose domains was military engineering.

The case of the ancient torsion-spring catapult is revealing. Weapons development was nothing new in antiquity, and, indeed, something like a technological arms race took place among craftsmen and sponsoring patrons to build the largest rowed warship. Philip II of Macedon and Greek kings in Syracuse, Rhodes, and elsewhere supported programs to develop and improve the catapult and a variety of ballistic machines. Sophisticated engineering research in the form of systematic tests took place at Alexandria to identify variables affecting the functioning of catapults and to create the most effective and efficient machines. The government sponsored this research, and scientists at Alexandria car-

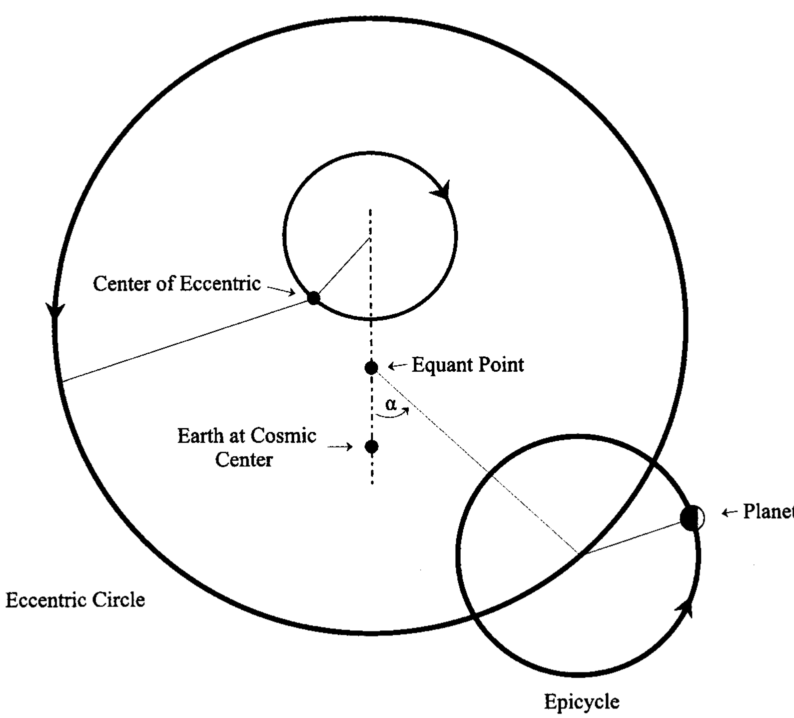


Fig. 5.2. Ptolemy's model for Mercury. Ptolemy deployed epicycles, eccentrics, and equants in elaborate and often confusing combinations to solve problems of planetary motion. In the case of Mercury (pictured here) the planet on an epicycle circle; the center of that circle revolves on a larger eccentric circle, the center of which moves in the opposite direction on an epicycle circle of its own. The required uniformity of the planet's motion is measured by the angle (α) swept out unvaryingly by a line joining the equant point and the center of the planet's epicycle circle. These techniques can be made to account for any observed trajectories. The intricate sets of solutions Ptolemy and his successors produced constituted gigantic "Ferris wheel" mechanisms moving the heavens.

ried out some of it. Although the mechanical tradition at Alexandria was less otherworldly than once thought, one must qualify the ways in which catapult research represents applied science in antiquity. Overall, the tests seem to have been entirely empirical, that is, executed by scientist-engineers perhaps, but without the application of any scientific theory or the exploitation of theoretical knowledge. After decades of patient effort and record-keeping the scientist-engineers at Alexandria created a practical and mathematically exact "catapult formula" that involved extracting cube roots and that specified the optimal dimensions for any ballistic machine and its projectile. With this formula Archimedes himself purportedly built the largest stone-throwing catapult on record. But the formula is simply a rule of thumb expressed in mathematical terms. Development of the catapult is better thought of as applied engineering research.

Some scientific instruments existed in antiquity—notably finely crafted astronomical clockwork and other observing devices, where science and technology combined in the service, not of warfare or the larger economy, but of the scientific enterprise itself. As interesting and historically revealing as all these examples are, they do not belie the general point that ancient science on the whole had very little practical import, was not as a rule directed to practical ends, and had no significant impact on ancient engineering as a whole.

Technology in antiquity needs to be seen as a domain separate from ancient science, a robust world of farming, weaving, potting, building, transporting, healing, governing, and like myriads of crafts and techniques great and small that made up and maintained Hellenistic and Greco-Roman civilization. Hundreds of small new technologies and technological refinements occurred in the 800 years of the Hellenistic and Greco-Roman periods (such as a kickwheel added to the potter's wheel), but overall the technological bases of production did not change fundamentally during the period. Some industrial-style production occurred in a few fields like mining; and long-distance commercial movement of people and goods took place regularly. But most production remained craft-based and local, and artisans, traditionally secretive about knowledge of their skills, tended to monopolize practice without the benefit of writing, science, or natural philosophy.

While ancient science formed part of civilized life in towns, technology and engineering practice could be found everywhere in the ancient world, vigorously and expertly developed in great cities and towns, to be sure, but also in the countryside, where the practice of science and natural philosophy was notably absent. The engineer (*architecton*) was a recognized and employable social type in antiquity. A handful of individuals stood at the top rank of ancient engineering. The Roman Vitruvius, for example, worked as architect/engineer to the first Roman emperor, Augustus, at the turn of the first century CE, and he contributed to an engineering literature. However, most engineers and,

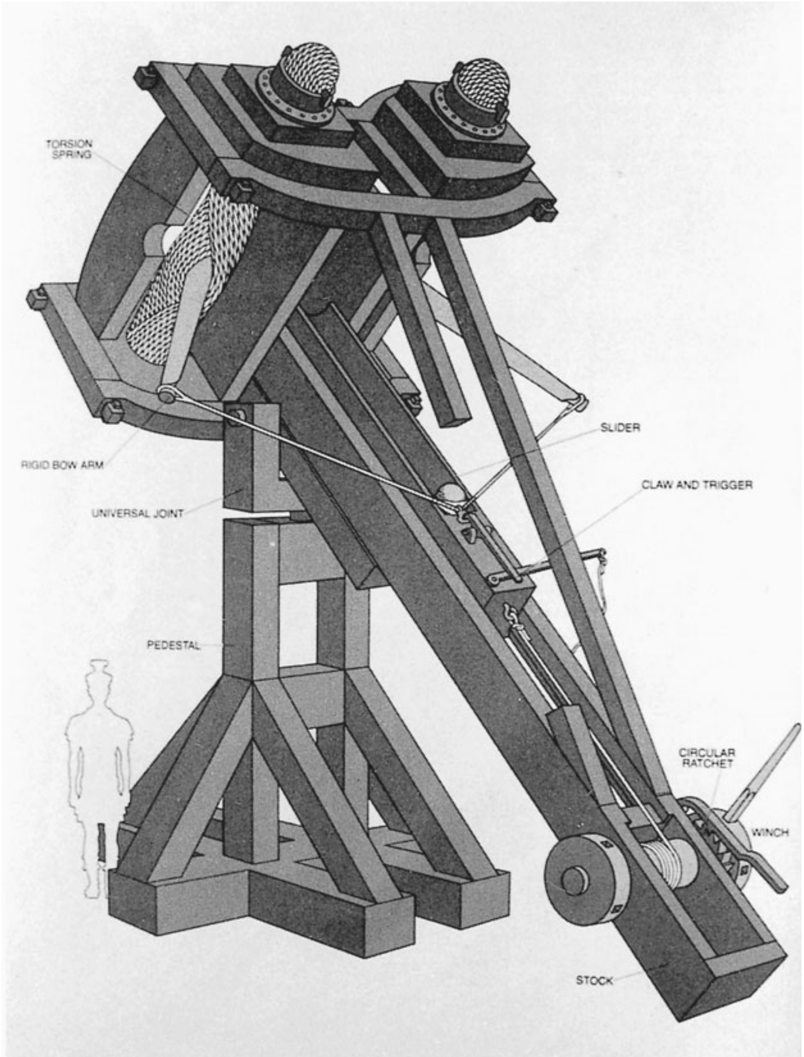
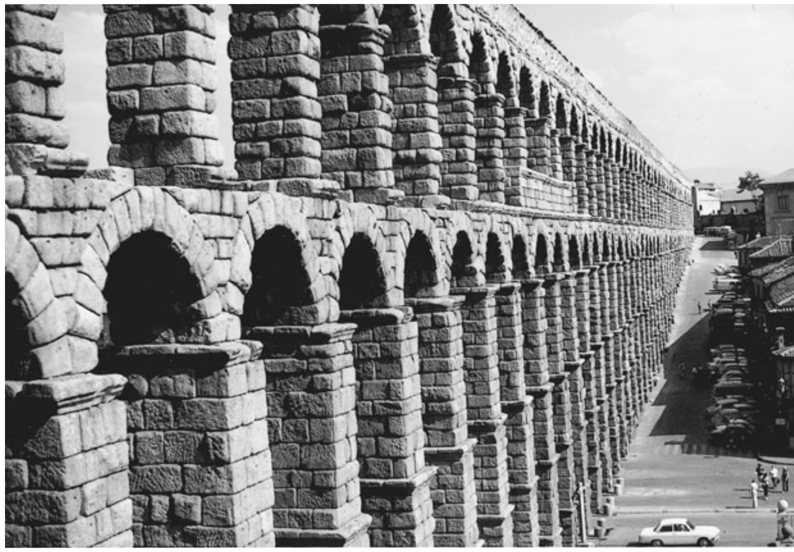


Fig. 5.3. The torsion-spring catapult. The Greeks under Philip of Macedon had begun to use ballistic artillery in the form of machines that could hurl large projectiles at an enemy. In some designs the action was produced by twisting and suddenly releasing bundles of elastic material. This large Roman model fired stones weighing 70 pounds. Hellenistic scientist-engineers experimented to improve the devices.

indeed, most artisans were anonymous practitioners plying trades at great remove socially, intellectually, and practically from the scientific world of Alexandria.

The Romans were the greatest technologists and engineers of the ancient world, and one can argue that Roman civilization itself represents one grand technological achievement. In the first centuries BCE and CE Roman military and political power came to dominate the whole of the Mediterranean basin and much of the Hellenistic world that had arisen in the east. (Mesopotamia remained beyond the reach of Rome.) The Roman empire grew up around several technologies. Military and naval technologies created the disciplined Roman legion and the Roman navy. The extensive systems of Roman roads and aqueducts provided an essential infrastructure. The expertise and sophistication of the Romans in matters of formal law may also be thought of as a social technology of no small import in running the empire. Less lofty per-

Fig. 5.4. Roman building technology. Roman engineers were highly competent in the use of the wedge arch in the construction of buildings, bridges, and elevated aqueducts. This Roman aqueduct in Segovia, Spain, is an outstanding example. The invention of cement greatly facilitated Roman building techniques.



haps, but no less important as a building block of Roman civilization, the invention of cement was a key new technology introduced by the Romans, one that made stone construction much cheaper and easier, and it literally cemented the expansion of the Roman empire. The fact that Rome produced known engineers, a few of whom wrote books (an uncommon practice among engineers), such as Vitruvius and Frontinus (35–103 CE), likewise testifies to the significance of engineering and technology to Roman civilization and vice versa.

While Roman engineering flourished, there was little Roman science. Very little Greek science was ever translated into Latin. For the sake of tradition, Roman emperors patronized the Museum in faraway Alexandria, but the Romans did not value, indeed they spurned, science, mathematics, and Greek learning in general. Some privileged young Romans learned Greek and toured and studied in Greece. But Rome itself produced no Roman scientist or natural philosopher of the first or even the second rank. This circumstance has proved a puzzlement for those who see science and technology as always and necessarily linked. The temptation has been to overemphasize those exceptional Romans who did write on matters scientific. The notable Roman poet Lucretius (d. 55 BCE), whose long poem *On the Nature of Things* advanced atomist notions, is one example. The great Roman compiler Pliny the Elder (24–79 CE), whose multivolume *Natural History* summarized as much of the natural world as he could document (the fabulous along with the commonplace), is another. For better or worse, Pliny's work remained the starting point for the study of natural history until the sixteenth century; that he devoted considerable space to the practical uses of animals and that he dedicated his *Natural History* to the emperor Titus suggests that, insofar as Roman science existed at all, familiar social forces were at play.

Greek scholars lectured in Rome. Greek doctors, particularly, found employment in Rome, more for their clinical skills than for their theoretical knowledge. The illustrious scientist-physician Galen of Pergamum (ca. 130–200 CE) was born, raised, and trained in Asia Minor and Alexandria, but climbed the ladder of medical success in Rome through gladiatorial and court circles, becoming court physician to the Roman emperor Marcus Aurelius. Galen produced a large and influential body of work in anatomy, physiology, and what we would call biology. He built on Aristotle and the Hippocratic corpus and he articulated rational and comprehensive accounts of the workings of the human body based on detailed anatomical analysis.

Galen's anatomy and physiology differ markedly from succeeding views in the European Renaissance and those held today, but that fact should not detract from the power and persuasiveness of his understanding of the human fabric. For Galen and his many successors, three different vital systems and as many *pneuma* operated in humans. He held that the liver and venous system absorbed nutrients and distributed a nourishing blood throughout the body. The brain and nerves distributed a psychic essence that permitted thought. The heart was the seat of innate heat which distributed a third, vital fluid through the arteries, thus enabling movement; the lungs regulated respiration and the cooling of the heart's innate heat. The circulation of the blood was a conceptual impossibility for Galenists because they believed that, except for a minor passageway in the heart where the nutrifying blood provided the raw material for the arterial spirit, veins and arteries were two entirely separate systems.

Galen was a prolific author, supposedly writing some 500 treatises, of which 83 survived antiquity. He remained the undisputed authority in anatomy and physiology into the early modern era. Galen exemplifies the continuing interaction between medicine and philosophy in the Hellenistic and Greco-Roman eras, but Galen was Greek, and the tradition out of which he emerged and to which he contributed was Hellenistic and not Roman. The phenomenal lack of any Roman tradition in mathematics or the natural sciences contrasts strongly not only with Roman engineering but also with the substantial record of Roman literary and artistic accomplishment in poetry, the theater, literature, history, and the fine arts. The names of Cicero, Virgil, Horace, and Suetonius alone suffice to indicate the extent to which literary and learned culture held a valued place in Roman civilization generally. The Roman case shows that a civilization of great social and technological

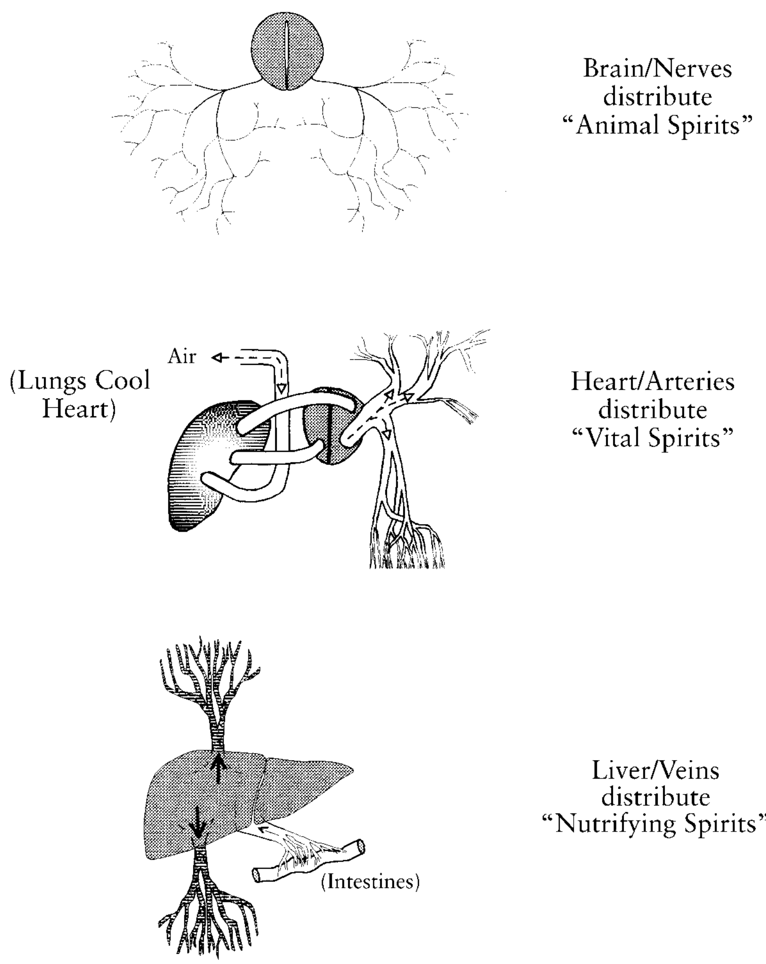


Fig. 5.5. Galenic physiology. Ancient physicians and students of anatomy separated the internal organs into three distinct subsystems governed by three different "spirits" functioning in the human body: a psychic essence permeating the brain and the nerves, a vivifying arterial spirit arising in the heart, and a nutrifying venous spirit originating in the liver.

complexity could thrive for centuries essentially without theoretical science or natural philosophy.

Decline and Fall

The causes of the marked decline of science and natural philosophy at the end of the Greco-Roman era have long been debated among historians of science. Not all agree even about the facts. Some claim the decline can be dated from 200 BCE in the Hellenistic era; others say it only began after 200 CE in the Greco-Roman period. Certainly, not all scientific and natural philosophical activity came to a halt after the second century CE. Still, ancient science seems to have run out of steam in late antiquity. Generally speaking, less overall activity took place, and the level of scientific originality declined as time went on. Intellectual labor was increasingly directed less toward discovering new knowledge than toward preserving old knowledge. This characteristic state of affairs gave rise to generations of compilers and commentators. Oribasius at Constantinople, for example, in the middle of the fourth century CE, wrote a formidable medical compendium of seventy volumes. (It is notable, but hardly surprising in this regard, that medicine displayed greater historical continuity in antiquity than did ancient science or natural philosophy.) Whatever animated the pursuit of science seems to have disappeared. Eventually, the desire merely to preserve past knowledge fell off. Increasing skepticism arose about even the possibility of secure knowledge, and magic and popular superstitious beliefs gained ground. The substance and spirit of Greek scientific accomplishment in its Hellenic and Hellenistic modes gradually faded away in late antiquity.

Several explanations have been proposed to explain why. One possible explanation points to the lack of a clear social role for science and scientific careers. Science was weakly socialized and institutionalized in the ancient world, and it largely lacked an ideological or material basis of support in society. No employment was available for individuals in their capacities as scientists or as natural philosophers, and the separation of science and natural philosophy from *philosophy* itself that developed in the Hellenistic period further undercut any social role for the scientific enterprise.

A related explanation has to do with the ancient economy and the separation of science and technology in antiquity. That is, given slavery, the relative cheapness of human labor, and the ideology that natural knowledge should not be applied to practical ends, little incentive existed to employ scientists or to search for practical outcomes of abstract understandings of nature. In other words, by excluding the possible utility of natural knowledge, the social role and social support for science were undermined.

Historians have also made a strong case that the flourishing of various religious cults and sects in late antiquity did much to weaken the authority and vitality of ancient scientific traditions. To varying degrees the many cults of late antiquity were anti-intellectual in their approach, and they represented intellectual and spiritual competition with traditional knowledge of nature. The cult of the Greek fertility goddess Demeter and the cult of the Egyptian goddess Isis attracted wide followings. Popular among officials of the Roman empire, Mithraism, a late oriental mystery cult worshiping the Persian god of light, Mithras, embodied arcane and secret astrological and astronomical knowledge. And growing out of messianic Judaism, the most successful new cult was Christianity.

Official toleration of Christians in 313 CE, the emperor Constantine's conversion to Christianity in 337, and the declaration in 391 of Christianity as the official state religion of the Roman Empire marked the extraordinary social and institutional success of the Christian church. Experts debate the effect of Christianity on ancient science, but with its heavy theological orientation, its devotional stress on the religious life, and its emphasis on revelation, the afterlife, and the second coming of Christ, the early Christian church and the church leaders who fashioned it displayed greater or lesser degrees of hostility, skepticism, ambivalence, and/or indifference toward pagan culture in general and toward science and inquiries into nature in particular. To cite only one example, Saint Augustine (354–430 CE) railed against natural philosophy and "those whom the Greeks call *physici.*" On a more mundane level the church became firmly institutionalized in ancient civilization and a formidable institutional presence at every level of society. Church bureaucracy and administration offered employment and careers, which had the effect of draining talent, intellectual and otherwise, which previously might have been recruited for the Museum at Alexandria or for science in general.

Historians of technology have asked why no industrial revolution developed in antiquity. The simple answer seems to be that there was no need, that contemporary modes of production and the slave-based economy of the day satisfactorily maintained the status quo. The capitalist idea of profit as a desirable end to pursue was completely foreign to the contemporary mentality. So, too, was the idea that technology on a large scale could or should be harnessed to those ends. An industrial revolution was literally unthinkable in antiquity.

Alexandria and its intellectual infrastructure suffered many blows from the late third century onward. Much of the town was destroyed in 270–75 CE in Roman efforts to reconquer the city after its momentary capture by Syrian and Arab invaders. Christian vigilantes may well have burned books in the fourth century, and in 415 with the murder by Christian fanatics of the pagan Hypatia, the first known female mathematician and the last known stipendiary of the Museum, the centuries-old Museum itself came to an end. Later, the initial Islamic conquerors effected further depredations on what remained of the Library at Alexandria. Elsewhere, in 529 CE the Christian Byzantine emperor Justinian ordered the closing of the Platonic Academy in Athens.

The Roman Empire split into its western and eastern divisions in the fourth century CE. In 330 CE, Constantine the Great transferred the capital of the empire from Rome to Constantinople, modern-day Istanbul. Waves of barbarian tribes pressed in on the western empire from Europe. Visigoth invaders sacked Rome for the first time in 410 CE. Other Germans deposed the last Roman emperor in Italy in 476 CE, a date that marks the traditional end of the Roman Empire. While the latinized West Roman Empire fell, the Hellenized East Roman Empire—the Greek-speaking Byzantine Empire—centered in Constantinople, endured, indeed flourished. But, the fortunes of Byzantium declined in the seventh century as its glory and granaries contracted before the armed might of ascendant Islamic Arabs. Pouring out of Arabia after 632 CE, the followers of the Prophet Mohammed conquered Syria and Mesopotamia. They captured Egypt and Alexandria in 642 CE and pressed in on Constantinople itself by the end of the century. Science and civilization would continue to develop in Muslim Spain, in eastern regions, and throughout the Islamic world, but by the seventh century CE the era of Greek science in antiquity had clearly come to an end.

The Roman West, which included much of Europe, had always been underdeveloped compared to the East. Decline, intellectual and otherwise, at the end of antiquity affected the West much more than the East, where greater continuity prevailed. Indeed, the words *disruption* and *discontinuity* aptly describe "western civilization" at the end of Greco-Roman antiquity. The population of Italy, for example, dropped by 50 percent between 200 and 600 CE. An era had ended, and surely to contemporaries no promise of renewal seemed to be forthcoming. The late Roman author and senator Boethius (480–524 CE) knew that he stood at a historical crossroads, and his case is a poignant one on that account. Boethius was exceptionally well educated and fully the inheritor of the classical tradition of Greek and Latin antiquity that stretched back a millennium to Plato, Aristotle, and the pre-Socratics. Yet he held office and attended not a Roman emperor, but the Ostrogoth king in Rome, Theodoric. Imprisoned for many years by Theodoric, Boethius made every effort to pass on to the succeeding age as much of antiquity's accumulated knowledge as he could. He wrote short elementary handbooks on arithmetic, geometry, astronomy, mechanics, physics, and music. In addition, he translated some of Aristotle's logical treatises, some Euclid, and perhaps Archimedes and Ptolemy. In prison, he also wrote his immortal meditations, *On the Consolation of Philosophy,* which proved small consolation indeed. Theodoric had Boethius executed in 524.

Historians interested in the European Middle Ages and in the history of science in the Middle Ages often point to Boethius and his compeers to indicate the extent to which knowledge from classical antiquity passed directly into the stream of European history and culture. Cassiodorus (488–575), a Roman like Boethius, who influenced the early monastic movement, is regularly cited in this connection, as are the later learned churchmen Isidore of Seville (560–636) and the Venerable Bede (d. 735). There is much of interest about these men and their circumstances, but the Latin West inherited the merest crumbs of Greek science. From a world perspective, what needs to be emphasized is the utterly sorry state of learning among the Christian barbarians of Europe and the Latin West in the early Middle Ages. After the fall of Rome literacy itself virtually disappeared, and knowledge of Greek for all intents and purposes vanished. Isidore of Seville apparently thought the sun illuminated the stars. Two eleventh-century European scholars, Regimbold of Cologne and Radolf of Liège, could not fathom the sense of the elementary proposition from geometry that "the interior angles of a triangle equal two right angles." The terms "feet," "square feet," and "cubic feet" had no meaning for them.

How and why the scientific traditions of Greek antiquity took hold in western Europe centuries later require separate explanations and a return to the world stage.