CHAPTER 4

Greeks Bearing Gifts

Ancient history displays a remarkable singularity in what has sometimes been termed the "Greek miracle." Just to the west of the Near Eastern civilizations, around the shores of the Aegean Sea, Greek-speaking peoples originated a unique civilization.

Given its proximity to Egypt and Mesopotamia, Greek civilization derived some of its traits from its older neighbors. But those traits took root in a habitat sharply different from the semiarid flood plains of Egypt and Mesopotamia. Instead of a centralized kingdom, Greek civilization arose as a set of decentralized city-states, and it retained its loose structure until Alexander the Great (356–323 BCE) unified Greece in the fourth century BCE. Its pre-imperial period, from 600 to 300 BCE, is known as the Hellenic era, while the period following Alexander's conquests has been designated as the Hellenistic.

During the Hellenic period Greek science took an unprecedented turn as natural philosophers, unsupported by the state and uncommitted to any program of useful knowledge, developed a series of abstract speculations about the natural world. Then, with Alexander's conquest of the wealthy districts of the East, Greek science entered its Golden Age through a merger of its theoretical spirit with the bureaucratic pattern of institutional patronage.

Several features characterize Hellenic science. The most remarkable was the Greek invention of scientific theory—"natural philosophy" or the philosophy of nature. Early Greek speculations on the cosmos and the disinterested Hellenic quest for abstract knowledge were unprecedented endeavors. They added a fundamental new element to the definition of science and shifted the direction of its history. In launching their novel intellectual enterprise, early Greek natural philosophers raised fundamental questions that proved highly influential and continue to be asked today.

A second notable feature of Hellenic science concerns its institutional status. At least in the period down to Alexander the Great, state patronage for Greek science did not exist and, unlike the Near East, there were no scientific institutions. Some informal "schools"—intellectually very important ones—did appear in classical Greek culture, but these operated more in the vein of private associations or clubs rather than educational institutions. No public support or funding existed for schools of higher learning, libraries, or observatories, nor did scientists or natural philosophers receive public employment. Quite unlike his state-sponsored counterpart, the Greek natural philosopher was an independent operator. Although we know little of their private lives, it appears that early natural philosophers either possessed independent wealth or earned a living as private teachers, doctors, or engineers since there was no social role for natural philosophers or scientists as such. Hellenic science thus floated in a sociological vacuum to the point where the utterly impractical and apparently meaningless private investigations of its practitioners sometimes excited animosity and ridicule.

In the East, knowledge had been turned to practical ends and purposes. But in Hellenic Greece a distinctive ideology stressed the philosophical dimension of knowledge and a detachment from any social or economic objectives. In an influential passage in his Republic (ca. 390 BCE), for example, Plato mocks the idea that one should study geometry or astronomy in pursuit of practical benefits for agriculture, military affairs, navigation, or the calendar. Plato insisted on separating the pursuit of natural knowledge from the lesser activities of the crafts and technology. In this regard it might be said that the Greeks undertook natural philosophy as play or recreation or to fulfill higher goals concerning the life of reason and philosophic contemplation. By contrast, no comparable disinterested intellectual endeavor had been evident in the scientific cultures of the ancient hydraulic civilizations. Finally in this connection, whereas a utilitarian pattern appeared in each of the pristine civilizations, Hellenic natural philosophy appeared once, in Hellas, the result of a singular set of historical circumstances. In sum, Hellenic natural knowledge represents a new sort of science and scientific activity—self-consciously theoretical inquiries into nature.

Recent research, while not taking away from the glories of early Greek natural philosophy, has tended to set the Greek scientific enterprise in a larger, more pluralistic cultural context. It used to be thought, for example, that science and rationality arose almost miraculously from the dark world of religion and myth prevailing before the Hellenic. Today, historians emphasize that ancient Greece was not culturally insulated from the East or from the "barbarian" world beyond Greece itself. In particular, recent interpretations stress the influence of Egyptian civilization on the development of Hellenic culture around the Aegean Sea. Within the Hellenic world the continuation of popular beliefs in magic, folklore, alchemy, astrology, and religious mysticism of one variety or another represented intellectual competition to relatively secularized scientific knowledge.

Roots

The appearance of Greek science and natural philosophy may seem less surprising than it once did, but the question remains of how to account for the rise of natural philosophy in ancient Greece. Greece was a so-called secondary civilization, arising on the periphery of Egypt and Mesopotamia, but ecologically and economically very different from the principal centers of civilization in the Near East and elsewhere. (See map 4.1.) Whereas these pristine civilizations arose on the basis of hydraulic agriculture, food production and farming in the Greek city-states depended almost wholly on seasonal rainfall and runoff from mountain snow. The Greeks did not disdain waterworks, as research has shown, but these remained small scale since Greece lacked a great river and a large, productive flood plain. Furthermore, Neolithic deforestation and erosion had already degraded the ecology and productive capabilities of Greece to the extent that only comparatively low population densities could be supported. The spawning of scores of Greek colonies by a constant flow of emigrants around the Mediterranean in the eighth through sixth centuries BCE testifies to these ecological and cultural pressures. Classical Greece could not feed itself and depended on grain imports from abroad. The relatively poor agrarian economy of ancient Greece sustained itself on goat and sheep husbandry and on cultivating olive trees and grapevines which flourish on marginal soils by tapping subsurface water. The secondary products of wine and olive oil gave the Greeks something to trade and, as a result, Hellenic civilization acquired a maritime, mercantile, and outward-looking cast.

Just as the mountains of Greece compartmentalized the land in separate valleys, Hellenic civilization was politically decentralized and fragmented into small, independent city-states. The government of a city-state in a region with a limited and eroded agricultural base could never concentrate enormous wealth like that of an Egyptian pharaoh to patronize a pervasive bureaucracy that bent every social and cultural activity toward the interests of the state.

The Greeks are famous for the level of their political debate about law and justice and for their analysis of kingdoms, aristocracies, democracies, tyrannies, and the like. A small step separates rational debate about political constitutions from inquiring into the constitution of nature—and vice versa, as the later history of science was to show. These political debates may indeed have provided one route to the origins of Greek science. It may be impossible to reach an understanding of exactly *why* a new scientific culture came into being in the unique habitat of Hellas. (If Ionia and Athens had remained as bereft of science as, say, Corinth and Sparta, would there be any grounds for surprise?) But once a scientific culture arose in ancient Greece it was shaped by a society that attached no social value to scientific research or


Apollonia
BLACK SEA
Heraclea
Abdera
Stagira
ITALY
Thasos
Cyzicus
Lampsacus
Torentum
ASIA MINOR
AEGEAN SEA
Pergamum
GREECE
Lesbos
Clazomenos
Croton
Chios
Colophon
Thebes
Ephesus
MAGNA GRAECIA
Samos
IONIA
Athens
Miletus
Corinth
SICILY
Cos
Sparta
Cnidus
Acragas
Syracuse
CYPRUS
CRETE
HELLENISTIC KINGDOMS
Macedonia
Kingdom of the Selucids
Kingdom of the Ptolomies
Cyrene
Alexandria

instruction and that provided no public support for schools of higher learning.

Greek science did not originate in Greece, but in Asia Minor on the (then-) fertile Mediterranean coast of present-day Turkey, at first in the city of Miletus and later in several other cities of the region known as Ionia. In the seventh century BCE Ionia was the center of Greek civilization while the Greek mainland was decidedly the province. Lying on the eastern shores of the Aegean, it had more fertile land and received more rainfall than mainland Greece. Ionia remained more urbanized and economically superior to Greece proper for two centuries. Not surprisingly, the majority of the first natural philosophers hailed from Ionia.

The Ionians and the entire collection of early Greek natural philosophers are known as the pre-Socratics, that is, thinkers active in the formative period of Greek philosophical and scientific thought before Socrates (470?–399 BCE). (See table 4.1.) Greek natural philosophy is usually said to begin with Thales of Miletus, who lived from about 625 to about 545 BCE. Thales is a test case for historical interpretation, for we have nothing from Thales himself and are wholly dependent on secondary reports. Our view of Thales is thus refracted through both the biases of ancient commentators and our own interpretative frames. We do know that he came from Miletus, a vibrant trading city on the Ionian coast of Asia Minor, and that he was later crowned as one of the seven "wise men" of archaic Greece, along with his contemporary, the lawgiver Solon. Thales was probably rich, and he probably traveled to Egypt, from where he is said to have brought geometry to the Greek-speaking world. As Plato reports, maliciously perhaps, Thales and his philosophy earned a reputation for unworldliness: "A servant-girl is said to have mocked Thales for falling into a well while he was observing the stars and gazing upwards, declaring that he was eager to know things in the sky, but that what was behind him and just by his feet escaped his notice." By the same token, according to Aristotle, Thales exploited his knowledge of nature through an astute scientific observation of a forthcoming harvest in order to corner the market on olive presses and thus to demonstrate that philosophers could be rich and useful, if those were their concerns. Thales allegedly also applied his acute scientific knowledge in wartime to help King Croesus ford a river in 547 BCE. In the end, the social role of wise man or magus probably befits Thales better than that of the "first scientist," which he is often called, if by "scientist" one has more modern social models in mind.

That we know Thales's name and these details about his life unexpectedly reveals something significant about his natural philosophy and about the subsequent development of science. Thales's claims about nature were just that, *his* claims, made on his own authority as an individual (with or without other support). Put another way, in the tradition stemming from Greek science, ideas are the intellectual prop-

Map 4.1. The world of ancient Greece. Greek civilization originated as a cluster of small city-states around the Aegean Sea. Greek science first arose in towns along the Ionian coast of Asia Minor. After the conquests of Alexander the Great in the fourth century BCE the Greek world stretched from Egypt to the borders of China, forming the largest empire in the ancient world. After Alexander's death in 323, his empire *(inset)* collapsed into three states: Macedonian Greece, Ptolemaic Egypt, and the Seleucid Kingdom in Mesopotamia. *(opposite)*

Table 4.1
The Pre-Socratic Natural Philosophers

The Milesians	
Thales	fl. 585 BCE
Anaximander	fl. 555 BCE
Anaximenes	fl. 535 BCE
Empedocles of Acragas	fl. 445 BCE
The Pythagoreans	
Pythagoras of Samos	fl. 525 BCE
Philosophers of Change	
Heraclitus of Ephesus	fl. 500 BCE
Parmenides of Elea	fl. 480 BCE
The Atomists	
Leucippus of Miletus	fl. 435 BCE
Democritus of Abdera	fl. 410 BCE
Socrates of Athens	470?–399 BCE
Plato of Athens	428–347 BCE
Aristotle of Stagira	384–322 BCE

erty of individuals (or, less often, close-knit groups) who take responsibility and are assigned credit (sometimes by naming laws after them) for their contributions. This circumstance is in sharp contrast with the anonymity of scientists in the ancient bureaucratic kingdoms and, in fact, in all pre-Greek civilizations.

Thales made claims about nature, including his idea that the south-blowing Etesian winds cause the Nile flood. Another theory of his held that the earth floats on water like a log or a ship and that the earth quakes when rocked by some movement of the water. Only a hundred years after Thales, Herodotus savagely attacked these ideas, and to the modern scientific mind they may seem oddly primitive notions. But they are nonetheless extraordinary in several important regards. For one, the explanations offered by Thales are entirely general; they seek to account for *all* earthquakes and *all* Nile floods, and not only a single case. In a related way, Thales invokes no gods or supernatural entities in his explanations; to use the stock phrase, he "leaves the gods out." Thus, "hail ruined my olive crop" not as punishment because I offended Zeus or Hera in a particular instance, but accidentally because in all instances—mine unfortunately included—hail results from natural processes that involve the freezing of water in the atmosphere. Note that a feature of Greek natural philosophy—the "discovery of nature"—required objectifying and demystifying nature, in order that theories might be proposed regarding nature in the first place. That is, "nature" had to be defined as an entity to be investigated; the concept may appear self-evident to us, but it was not necessarily so to our scientific forebears. "Naturalistic" explanations first posit the phenomenon in question to be a regular part of some external nature and hence a natural phenomenon, then account for the phenomenon also in terms of nature. Thus for the Nile, naturally occurring winds are invoked to explain the natural phenomenon of flooding. Interestingly in the case of earthquakes, Thales employs analogies to what we see in the world (ships, floating logs) in his explanation. It is far from the case, however, that Thales or (most of) his successors were atheists or irreligious; in fact, Thales also taught that the world is divine and "full of gods" and that the magnet possesses a "soul." There is no contradiction, however, for despite whatever homage is due the gods, Thales sets the natural world off both as somehow separate from the divine and as something comprehensible by the powers of human intellect.

Thales is known for his view that the world is composed of a primordial watery substrate. This deceptively simple pronouncement represents the first attempt to say something about the material "stuff" making up the world around us. It marks the beginning of matter theory—that line of scientific theorizing concerned with the makeup of the physical world below the level of ordinary perception. In asking about the material basis of things early in the sixth century BCE, Thales became the founding father of the first of the "schools" of Greek natural philosophy mentioned above, the Milesians. This Milesian school and its tradition of matter theory are an important element of pre-Socratic thought, but consideration of the intellectual dynamic driving the Milesians reveals another feature of the enterprise of early Greek science: the rise of science as rational debate. In a word, the Milesian philosophers disagreed, and they used reason, logic, and observation to attack the ideas of others and to bolster their own propositions.

Thales's notion that water is the primary substance had its problems, notably to explain how water could give rise to fire, its opposite, water and fire being mutually destructive, as in fire boiling away water or water quenching fire. Anaximander of Miletus (flourished 555 BCE) dealt with this problem in the generation following Thales by rejecting water as the underlying agent and by putting forth the much vaguer notion of some "boundless" or formless initial state (the *Apeiron*) out of which duality and the world grew. By allowing duality to emerge from unity, as it were, Anaximander's "boundless" explained hot and cold, which Thales could not, but the concept of the "boundless" remained forbiddingly abstract and metaphysical. The next Milesian, Anaximenes, responded to this difficulty and to the same general question around 535 BCE. His answer was to suggest air (or the "*pneuma*") as the primeval element. More down to earth, this suggestion would also seem to suffer from the problem of opposites that troubled Thales's water theory, except that Anaximenes posited two conflicting *forces* in the universe, rarefaction and condensation, which variously condensed air into liquids and solids and rarefied it into fire. The tradition of the Milesian school culminated a century later with the thought of Empedocles (fl. 445 BCE), who as an adult lived in Greek Italy. In a theory that remained influential for 2,000 years Empedocles postulated four primary elements—earth, air, fire, and water—and the attracting and repelling forces of (what else?) Love and Strife.

The pluralistic and abstract character of natural knowledge among the early Greeks is no better illustrated than by another pre-Socratic "school," the cult of the Pythagoreans. The Pythagoreans, centered in Italy, formed an organized religious brotherhood and sect, and individual innovator-adepts submerged their contributions to the collectivity by giving credit to their founding guru, Pythagoras (fl. 525 BCE), originally from the island of Samos off the Ionian coast. The Pythagoreans embodied a certain "orientalism" reminiscent of the master's sixth-century Persian contemporary, Zoroaster.

The Pythagoreans are famed for introducing mathematics into natural philosophy. Their mathematics was not the crude arithmetic of the marketplace or the practical geometrical procedures of the surveyor or architect, or even the exact mathematical tools of Babylonian astronomers. Rather, the Pythagoreans elevated mathematics to the level of the abstract and the theoretical, and they made the concept of number central to their view of nature. In its way, number was the Pythagorean response to the Milesian question about the material stuff of the world. In focusing on number, the Pythagoreans introduced potent notions of idealism into natural philosophy and science—the idea that some more perfect reality accessible through intellectual understanding underlies the observed world of appearances. Put crudely, the real world contains no perfect triangles, no absolutely straight lines, or numerical abstractions; such entities exist only in the realm of pure mathematics. That the Pythagoreans and their intellectual successors thought that such mathematical perfection somehow constitutes the world (or even that it is useful to think so) inaugurated a whole new way of thinking about nature, and it launched the great tradition of mathematical idealism that has been so powerful a current in scientific thought since then.

Pythagoras is supposed to have achieved the profound insight of mathematical order in the universe in considering musical strings and the tones they sound; half the length producing the octave above, one-third producing the higher fifth tone, and so on. Based on this unexpected correlation between small integers and the real world, Pythagoras and his followers extended their mathematical investigations. Some of their results, such as their classification of odd and even numbers, seem unexceptional to us; others, such as a sacred triangle (the *Tetractys*) representing the sum of the numbers 1, 2, 3, and 4 (= 10), or their association of the institution of marriage with the number 5 in joining the 2 of femaleness with the 3 of maleness, reflect what we would all too easily consider a bizarre numerology.

Of course, Pythagoras is credited with the discovery of the theorem in geometry that bears his name. It says that for any right triangle (to use the algebraic formulation) $a^2 + b^2 = c^2$, where c is the hypotenuse of the triangle and *a* and *b* are the legs. Lurking in the Pythagorean theorem is a corollary that says that not all line lengths can be expressed as ratios or fractions of other unit lengths. Some pairs of lines (like a leg and the diagonal of a square) are incommensurable—that is, their ratio cannot be expressed by any pair of integers. To the Pythagoreans the square root of 2 was "*alogon,*" the unutterable. The discovery of irrationality was subversive of the Pythagorean commitment to integers and the program of investigating mathematical harmonies in the world, and, supposedly, knowledge of the irrational was therefore held as the innermost secret of the Pythagorean cult.

The more fundamental point to be made about these discoveries is the role of mathematical proof in demonstrating their certainty. The invention of deductive reasoning and proof, wherein even the most skeptical auditor is forced step by step to the inevitable Q.E.D. ("thus proven") at the end, was a remarkable innovation in the histories of mathematics, logic, and science. The Egyptians knew of Pythagorean triplets (whole numbers obeying the Pythagorean theorem, as in 3-4-5 right triangles), and the Babylonians prepared tables listing them. But no one until the Pythagoreans saw in them a theorem to be proved. Rigorous mathematical demonstrations did not appear full-blown with the Pythagoreans, and the process of developing an axiomatic and deductive plane geometry continued until Euclid compiled his *Elements* around 300 BCE. Nevertheless, to the early Pythagoreans goes the credit for studying mathematics as natural philosophy, for turning Greek mathematics away from practical arithmetic to pure arithmetic and geometry, and for developing the proof as a means and model for justifying claims to knowledge.

The different traditions represented by the Milesians, the Pythagoreans, and their successors make plain that Greek natural philosophy in the pre-Socratic period lacked an agreed-upon unity and was fragmented into different schools of thought. In this connection two other major groups of pre-Socratic natural philosophers need to be mentioned at least briefly: the atomists and the so-called philosophers of change. The atomists, notably Leucippus of Miletus (fl. 435 BCE) and Democritus of Abdera (fl. 410 BCE), responded in their way to the Milesian challenge of a century earlier by imagining that the world is composed of atoms, the least reducible, indivisible particles of matter. These theorists supposed that differences in the shape, position, motion, and arrangement of atoms in the void are the root cause of the differences we see in objects around us. Ancient atomism faced a grave difficulty in explaining how random atoms could assume any coherent or lasting pattern in nature other than by cosmic accident, and atomist philosophy thereby earned a reputation for atheism. Some atomist demonstrations designed to illustrate the corporeality of air (a bottle of air held underwater) may be viewed as early scientific experiments, but ones whose purposes were to illustrate and not to test. Atomism

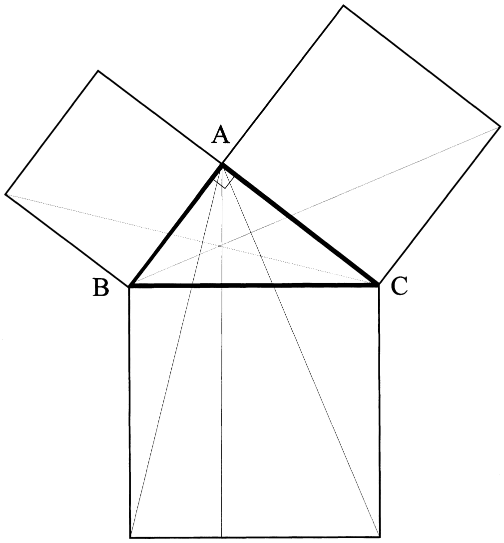

Fig. 4.1. The Pythagorean theorem. Although Pythagorean triplets (like 3-4-5) were recorded by Babylonian scribes, the Pythagorean theorem ($AB^2 + AC^2 = BC^2$) was first proved in Euclid's *Elements*. When the nineteenth-century philosopher Schopenhauer saw the diagram, he remarked, "That's not a proof, it's a mousetrap."

attracted a small following, notably in the person of the Roman poet Lucretius, but the movement was decidedly a minor branch of thought until its revival in seventeenth-century Europe and the emergence of modern atomic theories in the nineteenth century. Indeed the attention usually given to ancient atomism reflects our interests more than the ancients'.

The pre-Socratics did not limit their inquiries to the inanimate world around them, but also initiated natural philosophical investigations of the living world. Alcmaeon of Croton (fl. 500 BCE), for example, reportedly undertook anatomical research and dissected merely for the sake of learning.

Heraclitus of Ephesus (fl. 500 BCE) and Parmenides of Elea (fl. 480 BCE) are labeled the "philosophers of change" because they initiated a great debate over the nature of what we experience as change in the world. Heraclitus held that change is perpetual, that everything flows, that the same river is never crossed twice. Parmenides countered with the radical notion that nothing changes, that change is nothing but an illusion, despite the apparent evidence of our senses. The debate was important because it made explaining change central to natural philosophy. While the Milesians and the Pythagoreans do not seem to have considered the question, after Parmenides it was unavoidable: not simply the world, but apparent *flux* in the world is what natural philosophy needs to explain. The Heraclitean-Parmenidean debate also raised fundamental questions about the senses and about how we can know things. In part these questions involved the psychology of perception (e.g., the stick that seems to bend in water, the red of a red apple) and the general reliability of the senses. On another level they dealt with whether and, if so, how knowledge can be based on the senses or indeed on anything at all. The consequence for natural science was that thenceforth not only did every claim to knowledge about nature formally have to be buttressed by its own internal evidence and reasoning, but it had also to be accompanied (either implicitly or explicitly) by a separate rationale as to why *any* evidence or reasoning might support any such claims.

Whereas science in the ancient bureaucratic kingdoms had been patronized by the state and, accordingly, held to strict standards of usefulness, the work of these Greek natural philosophers was its polar opposite—theoretical, abstract, and whimsical. There was, however, one field of Greek higher learning that was more akin to the social pattern of the ancient East, the Hippocratic medical tradition that arose in the Hellenic period—the collective body of medical literature credited to the great fifth-century physician Hippocrates of Cos (fl. 425 BCE). In the Hippocratic tradition, with its emphasis on reason, cautious observation, medical prognostication, and natural healing, one finds a good deal of natural knowledge and scientific thinking akin to that pursued by the natural philosophers. For example, articulating a view that remained influential into the nineteenth century of our era, Hippocratic theorists correlated the four elements (earth, air, fire, and water) with four bodily humors (blood, phlegm, yellow bile, and black bile), and then argued that health represents a balance between and among the humors. By the same token, the skepticism of Hippocratic medicine—the doubt that certain knowledge is even possible—set it apart from most of the speculations of natural philosophy. Ancient medicine remained more tied to practice and craft than natural philosophy, and "scientific physicians," such as they were, competed alongside many "schools" and diverse forms of healing arts that included magic, incantations, and dream cures.

Around the Greek world clearly identifiable medical institutions could be found, notably in the temples and cult centers devoted to Asclepius, the deified physician and supposed offspring of Apollo. Asclepieions, or healing centers, appeared in Cos, Epidauros, Athens, and elsewhere. Medical practice was not regulated in antiquity, and doctors were often itinerant. Medicine was a highly specialized trade, and practitioners could become wealthy. City-states contracted with doctors in wartime, but by and large Hippocratic and other doctors operated independently of the political state or any government bureaucracy.

Worlds of Pure Thought

Although early Greek natural philosophers initiated abstract inquiries into nature there was no unity to their endeavors, and nothing like sustained scientific research is evident in their traditions. That changed in the fourth century BCE with the two great intellectual syntheses of Plato and Aristotle.

Before Plato there was no consensus in Greek cosmology or astronomical theory. Instead, the pre-Socratic tradition was notorious for the diversity of the models proposed. In the sixth century BCE Anaximander of Miletus had hypothesized that the earth is a disk, floating naturally in space with humans living on its flat surface. There are wheels of fire in the heavens and the luminous heavenly bodies we see are really holes in the fire wheels; the wheel of the stars is closest to the earth, the wheel of the sun farthest; eclipses result from holes becoming blocked; and certain mathematical proportions govern the location of the heavenly wheels. This cosmological model is remarkable for just that, being a model—some simplified simulation of the real thing, a likeness we might construct. Anaximander's view is more sophisticated than Egyptian and Mesopotamian cosmologies as well as the succeeding model of Anaximines (who held that the earth is a table held up by air), in that Anaximander can account for what supports the earth, that is, the earth positioned in the middle of nowhere. The model of the Pythagoreans displaced the earth from the center of the cosmos and held that it (and probably the sun) went around some vague central fire and an even more mysterious counter-Earth. The mechanical and vaguely mathematical character of these models made them distinctly Greek inventions, but their advocates did not pursue any of their details.

The case of Plato of Athens (428–347 BCE) and his geometrical astronomy carries us past the founding era of the pre-Socratics and lands us solidly in classical fourth-century Greece. Plato was a pupil of Socrates, the fifth-century master who "called philosophy down from the skies." In his youth, Socrates is said to have been interested in natural philosophy, but he concluded that nothing certain was to be learned in the study of nature, and he focused his attentions instead on examining the human experience and the good life. But he offended the political authorities and was sentenced to death. After his execution in 399 BCE, the mantle of philosophy passed to Plato, who seemingly felt better prepared to make direct statements about the natural world. Plato formalized the enterprises of philosophy and natural philosophy by establishing a private school, his Academy at Athens (which survived for 800 years). Significantly, inscribed over the portals of the Academy was the motto, "Let no one enter who is ignorant of geometry."

Geometry was important to Plato and his philosophy as a form of intellectual discipline and as a model for all that was metaphysically abstract and perfect. Geometry was also key to Plato's matter theory, as he identified the fundamental elements of earth, air, fire, water, and an extra aether with the five so-called perfect solids, three-dimensional polyhedra each with identical regular polygonal faces, which geometers had proven could be only five in number. (See figure 4.2.) But Plato himself was a philosopher, not a serious geometer or mathematician. Nor was he an astronomer. He did not observe the heavens, and he disdained those who did. Nevertheless, in his *Timaeus* Plato presents a fairly complex model of the heavens, involving a central earth linked mechanically along a common axis to a series of spinning shells or spheres that carry around the various heavenly bodies. A mystical part of Plato's cosmology and a common philosophical opinion for centuries held that the heavens were alive and divine. Although the cosmology was influential, in most respects it was no advance over the previous models of the pre-Socratics. In one crucial particular, however, Plato exerted a profound and lasting effect on astronomy and the history of science: he set Greek astronomers to solving problems.

Plato believed that the heavenly bodies revolve in circles around a stationary earth. He held this opinion not because he observed that the sun, moon, planets, fixed stars, and everything in the heavens move in circular arcs across the sky once every 24 hours, which sensory evidence confirms. Nor did his belief that the heavens were essentially unchanging apart from their motion rest only on the reported experience of previous generations. Rather, Plato held his views concerning celestial motion on first principles. Because of their majesty and virtually divine status Plato believed that the heavens represent an embodiment of the eternal, transcendent, and perfect world of pure Form. Plato's world of the Forms constitutes an unchanging ideal reality, of which our changing world is only a pale and imperfect reflection. Therefore, circular motion was the only motion suitable to the heavens because the circle is a figure of constant curvature with no beginning or end. Because they faithfully mirrored the perfection of the world of the Forms, Plato likewise concluded that the heavens must necessarily move uniformly; uniform motion does not speed up or slow down, betraying the imperfection of change, but remains constant and undeviating. Uniform circular motion of heavenly spheres was not questioned thereafter in antiquity.

While most motions in the heavens do seem to be circular, some motions are plainly not circular and equally plainly not uniform. The daily movement of the stars, the annual trip of the sun around the heavens, and the monthly revolution of the moon are apparently circular, but other movements in the heavens are not, notably the movement of the planets or "wandering stars" as observed over a period of months. Relative to the background of the fixed stars, the planets slow in their courses, stop, move backwards, stop again, and move forward again, sweeping out great, noncircular loops in the sky. This was the great problem of the "stations and retrogradations" of the planets that Plato had uppermost in mind when, to use the famous phrase, he enjoined astronomers to "save the phenomena" with circles. Explaining the stations and retrogradations of the planets was the central problem in astronomy for nearly 2,000 years from Plato's era until after Copernicus in the sixteenth century CE.

Planetary motions presented difficulties, Plato believing the planets move in one way (circularly), and observation showing they move in another way (loopingly); there was an obvious conflict to be worked

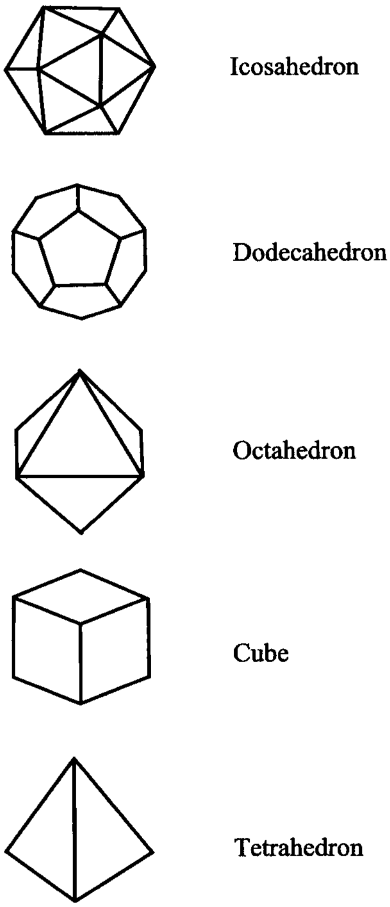

Fig. 4.2. The Platonic solids. Plato knew that there cannot be more than these five regular shapes (each with congruent equilateral polygonal faces), and he correlated these geometrical forms with the elements.

out, an area for research. But note the crucial converse: there is nothing at all problematical about the observed stations and retrogradations unless, like Plato and his followers, one thought the planets ought to move otherwise than they appear, in this case with uniform circular motion. The astronomical paradigm initiated by Plato represents more than the onset of some straightforward "research" into self-evident phenomena; Plato's prior philosophical (theoretical) commitments to Forms and circles made manifest the phenomena to be investigated. Thus Plato defined a problem in natural philosophy where none existed before. But the import of Plato's paradigm in astronomy goes further: he also defined for theorists and astronomers what constituted appropriate or acceptable solutions to the problem of the planets, that is, models that use uniform circular motion to produce apparently nonuniform appearances. Nothing else qualified as a solution to the puzzle.

Fourth-century astronomers took up the problem and formed a small but distinct tradition of research in astronomy and cosmology. Plato's student Eudoxus of Cnidus (fl. 365 BCE) was the first to respond. He proposed a model for the heavens which consisted of twenty-seven nested (homocentric) celestial spheres variously revolving around a central earth. The Eudoxean model made the universe into something akin to a grand cosmic onion. Some of the spheres were deployed to explain the apparent motion of the stars, sun, and moon, and each retrograding planet was assigned a system of four rotating spheres: one to account for daily motion, one for periodic motion through the heavens, and two, moving oppositely and tracing out a figure-8–like path of stations and retrogradations, known as the "hippopede." The model "worked," but there were problems with it. The observed inequality of the four seasons (they are not all the same length in days) was one, and to account for it a younger contemporary of Eudoxus, Callipus of Cyzicus (fl. 330 BCE), improved on the model by adding an extra sphere for the sun and raising the number of spheres to thirty-five in all. But the model was still imperfect, notably in not being able to explain how the universe could function mechanically with all those spheres spinning just below and above each other at different rates and inclinations. In the next generation Aristotle (384–322 BCE) tried his hand at this issue in technical astronomy, and, by inserting a number of counteracting spheres, he increased their number to fifty-five or fifty-six.

The Eudoxean model of homocentric spheres and the small research tradition associated with it hardly survived the Hellenic era, much less antiquity. In the final analysis the intellectual and conceptual problems afflicting Eudoxus's approach proved fatal. Those problems included difficulties explaining why the seasons are not the same number of days, why Venus varies in brightness, and why Venus, Mercury, and the sun should always stay close to one another. By the second century BCE astronomers were actively considering alternatives to homocentrism, and the culmination of ancient astronomy in the work of Claudius Ptolemy (fl. 150 CE) 500 years later shows only the vaguest relation to what Plato, Eudoxus, and their colleagues had in mind with their spinning sets of spheres.

This research tradition was nonetheless notable in several key respects. For one, the case makes evident how much scientific research at

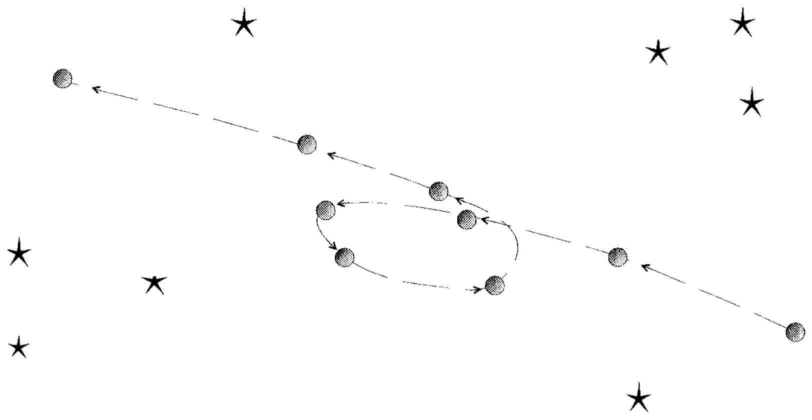

Fig. 4.3. Retrograde motion of Mars. To an observer on Earth, over a period of months Mars appears to reverse its direction as seen against the background of the fixed stars and then reverse it again to resume its forward trajectory. Accounting for these loops in terms of uniform circular motion defined a key problem that occupied astronomers for 2,000 years.

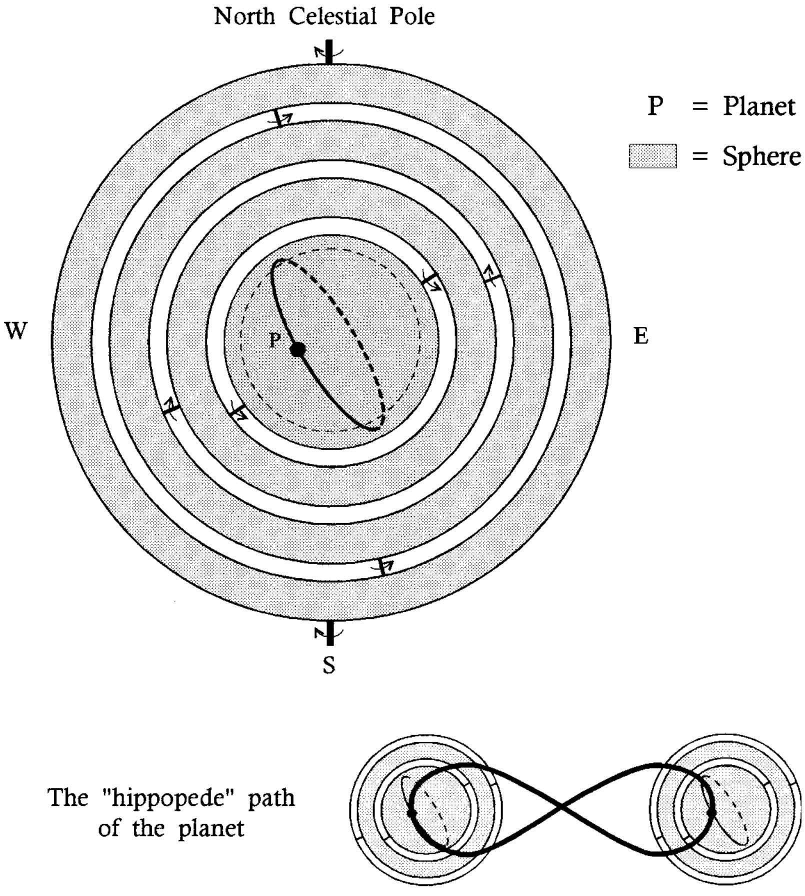

Fig. 4.4. Eudoxus's system of homocentric spheres. In Eudoxus's "onion" system, Earth is at rest in the center of the universe, and each planet is nestled in a separate set of spheres that account for its daily and other periodic motions across the heavens. From the point of view of an observer on Earth, two of the spheres produce the apparent "hippopede" (or figure-eight) motion that resembles the stations and retrogradations of the planets.

this level depends on consensus among scientific practitioners. It makes no sense, in other words, for Eudoxus, Callipus, and Aristotle to have taken up the detailed investigations just described unless they agreed that Plato's approach was basically correct. The instance makes plain once again the community-based nature of the scientific enterprise in its Greek as well as its bureaucratic guise. In some larger sense groups, not individuals, practice science. Finally, like their counterparts among anonymous Babylonian astronomers and astrologers, Eudoxus, Callipus, and Aristotle did not simply know things about nature, they were not simply manipulating nature, and they were not simply theorizing about nature. They were checking nature out in detail, along lines established by their general philosophical, metaphysical, and theoretical commitments. The arsenal of techniques pertinent to the human inquiry into nature had expanded considerably from the first paleolithic lunar tallies.

Enter Aristotle

Aristotle marked a watershed in the history of science. His work, which encompassed logic, physics, cosmology, psychology, natural history, anatomy, metaphysics, ethics, and aesthetics, represents both the culmination of the Hellenic Enlightenment and the fountainhead of science and higher learning for the following 2,000 years. Aristotle dominated scientific traditions in late antiquity, in medieval Islam, and in early modern Europe where his science and his worldview defined scientific methodology and the research agenda up to just a few centuries ago.

Born in the town of Stagira in Thrace in northern Greece in 384 BCE, Aristotle came from a privileged family, his father being royal physician to the king of Macedonia. In his teens Aristotle went to Athens to study with Plato, and he remained in Athens as a member of the Academy for 20 years until Plato's death in 347. He then traveled around the Aegean until 343, when King Philip II of Macedonia called him to his court to tutor his son, Alexander, who became Alexander the Great. After Alexander assumed the throne and began his world conquest in 336, Aristotle returned to Athens, where he founded his own school, the Lyceum. After Alexander's early death in 323, Aristotle found it politically prudent to leave Athens; he died the following year at the age of 62. The extensive writings that we commonly regard as Aristotle's were compiled to some extent during his lifetime and to some extent by disciples during the first two centuries after his death. In any event, several entire books have survived, unlike the fragments of the natural philosophers who preceded him. Indeed, Aristotle's commentaries on their work tell us much of what we know of his predecessors.

From a sociological point of view, as with all Hellenic scientists, Aristotle's research was undirected by any state authority, and he had no institutional affiliation. The Lyceum, his own place of teaching—a grove on the outskirts of Athens—was not formally established as a school during his lifetime. He was thus in some measure a footloose professor, one of the leisured intellectuals to whom, in fact, he attributed the achievements of theoretical science. The substance of his studies reflected his sociological standing—utterly abstract and of no possible use in engineering, medicine, or statecraft. Although he recognized the distinction between theoretical and practical knowledge, "speculative philosophers" and "[medical] practitioners," Aristotle confined his research to his private interests in the philosophy of nature. Even when he wrote on anatomy and biology, fields that might have lent themselves to useful studies applicable to the treatment of illness, he focused his objectives on the place of living beings in a rational cosmology. Similarly, his studies of the theory of motion, which remained influential until the seventeenth century, formed part of a program of purely theoretical research and were of no practical use in technical or economic applications.

Aristotle expressed himself in unambiguous terms concerning the relationship between science and technology. After humanity acquired the needed practical arts, leisured intellectuals cultivated pure science:

"When everything [practical] had been already provided, those sciences were discovered which deal neither with the necessities nor with the enjoyment of life, and this took place earliest in regions where men had leisure." Curiosity provided the motivation for the development of pure science: "For men were first led to study [natural] philosophy, as indeed they are today, by wonder. . . . Thus, if they took to philosophy to escape ignorance, it is patent that they were pursuing science for the sake of knowledge itself, and not for utilitarian applications." Aristotle's opinions are thus consistent with our studies that show the ratio of theoretical to practical orientations among known Hellenic scientists to have been roughly 4 to 1.

For the generations of natural philosophers who followed Aristotle the beauty and power of his achievement stemmed in large measure from the unity and universality of his worldview. He offered a comprehensive, coherent, and intellectually satisfying vision of the natural world and humanity's place in it, a vision that remains unequaled in scope and explanatory ambition.

Aristotle's physics, and indeed all of Aristotle's natural philosophy, is rightly said to represent the science of common sense. Unlike Plato's transcendentalism, Aristotle held that sensation and observation are valid—indeed, they represent the only route to knowledge. Time and again Aristotle's views conform with everyday observation and the commonplace experiences of the world we know (unlike modern science, which often contradicts plain observation and requires a reeducation of the senses before it can be accepted). Aristotle emphasized the sensible *qualities* of things, in opposition to the quantitative and transcendental approaches of the Pythagoreans or Plato's followers. Aristotle's natural philosophy was therefore more commonsensical and scientifically promising.

Aristotle's theory of matter provides an easy entrée to his overall vision of the cosmos. He followed Empedocles and Plato in adhering to the four elements of earth, air, fire, and water. But unlike Plato, who believed the elements to be fashioned of abstract polyhedrons, Aristotle took them to be composed of pairs of even more fundamental qualities: hot, cold, wet, and dry, projected onto a theoretically quality-less "first matter" or *prima materia*. Thus, as figure 4.5 illustrates, the qualities wet and cold make up the element water, hot and dry = fire, wet and hot = air, cold and dry = earth. Ordinary earth and all other composite bodies are mixtures of the pure elements, which are never found in an isolated state. And, again unlike Plato who found reality only in the transcendent world of the Forms, Aristotle held that the world we experience is materially real because objects in the world (such as tables and trees) are inseparable amalgamations of elemental matter and Form. Aristotle's matter theory is eminently rational and conformable to experience in, for example, explaining the boiling of water as a transformation of water into "air" by the substitution of the quality of hot

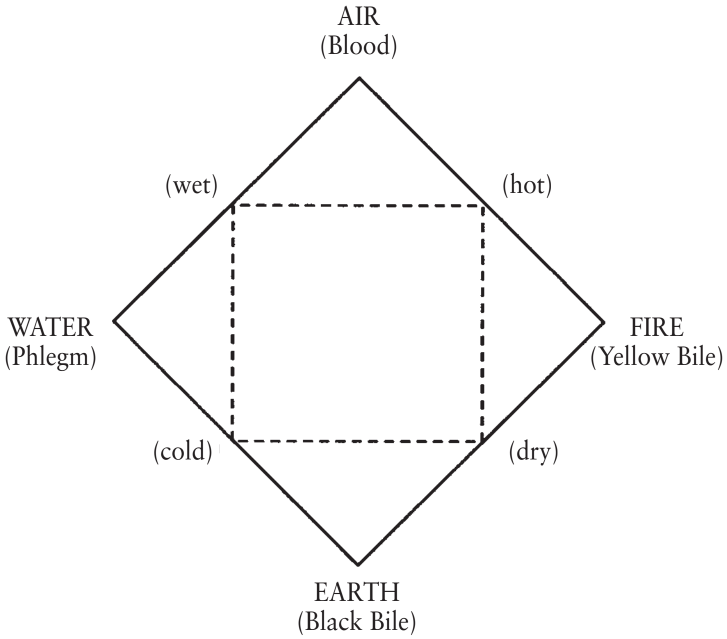

Fig. 4.5. The Aristotelian elements. In Aristotle's matter theory, pairs of qualities (hot-cold, wet-dry) define each of the four elements: earth, air, fire, and water. Substitute one quality for another, and the element changes. Each of the four elements also came to have an associated "humour," which connected Aristotle's views on matter with physiology and medical theory.

for the quality of cold. In this case the application of fire replaces the hot and wet of air for the cold and wet of water. It should be noted that such a qualitative theory of the elements provides a theoretical basis for alchemy, in that qualities are projected onto a quality-less *prima materia* or "first matter" and it thus becomes theoretically possible to strip, say, lead of its qualities and substitute the qualities of gold. The theory as much as the authority of Aristotle thus legitimated the alchemical enterprise.

For Aristotle, the physics of motion—change of place—is only a special case of change or alteration in general, such as growth, fermentation, and decay. He associated a motion with each element according to its nature: earth and water, being heavy, naturally move to the center of the universe (that is, the earth); air and fire, being light, naturally move away from the center. Nothing else is required to explain this intrinsic motion, just as nothing else is required by modern physics to explain inertial motion. Accordingly, each element seeks a place in the universe, its so-called natural place: earth at the center layered with concentric shells of water, air, and fire. Thus, his theoretical analysis accords well with what we observe in nature, with lakes and oceans atop the earth, with bubbles of air rising in water, with the atmosphere atop the waters and the earth, and with fire seeming to rise in the air and meteors to spark in the sky. Indeed, theoretically, the reason concentric shells of earth, water, air, and fire that surround the cosmic center are not perfectly spherical is that the terrestrial region represents the realm of change, violence, imperfection, and corruption. On Earth things get jumbled up, unlike the perfect, unchanging, and incorrupt-

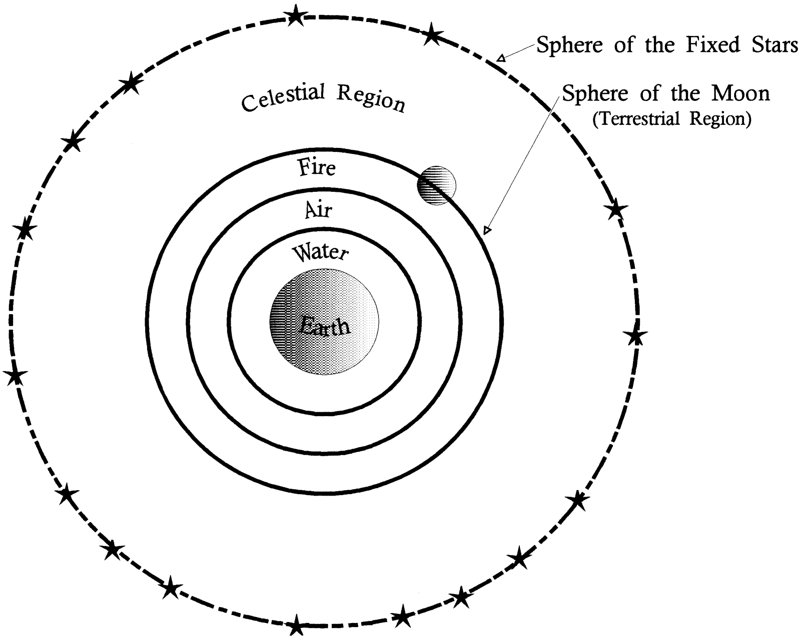

Fig. 4.6. The Aristotelian cosmos. According to Aristotle, each of the four elements has a "natural place" in the universe. In the terrestrial region (to the height of the moon), earth and water move "naturally" in straight lines downward toward the center of the cosmos (Earth), while air and fire "naturally" move in straight lines upward and away from the center. The sphere of the moon separates the terrestrial region, with its four elements (including fiery meteors and comets), from the celestial region—the realm of the fifth, "aetherial" element whose natural motion is circular. The stars and planets reside in the celestial region and take their circular motions from the aetherial spheres in which they are embedded.

ible celestial regions. In support of these conjectures Aristotle alluded to experimental confirmation. If one attempts to submerge a bag or bladder of air in water one will sense resistance against displacing air from its natural place into the realm of water, and if the balloon is forcibly submerged and then released it will spontaneously return to the realm of air.

In Aristotle's scheme of the world, the earth we live on is essentially spherical and totally motionless at the center of the universe. If, in some extraordinary thought experiment, we could displace the earth from the center, it would naturally return to the center and reassemble there, just as stones fall back to the center through air and through water in order to return to their natural place. Thus, Aristotle's geocentric cosmology—the idea that the spherical earth remains unmoving at the center of the cosmos—is backed up by the authority of physics and confirms our sensory experience of the earth at rest and the heavens in motion. Aristotle confirmed the sphericity of the earth, for example, from the shadow it casts on the moon during lunar eclipses; and he offered common-sense arguments against a moving earth, such as the observation that a ball thrown straight up falls back to its point of origin and is not left behind as the earth turns underneath.

Since different natural motions occur in the region of the earth (either up or down) and the region of the heavens (always circular), Aristotle's cosmology makes a sharp distinction between the physics of the two regions. When terrestrial objects move naturally, that is, without the motion being started or sustained by a living or external mover, they move either up or down, toward or away from the center of the earth, depending on whether they are heavy or light. The terrestrial or sublunary realm is defined as the world below the orbit of the moon, wherein the four elements seek their natural place. The heavens above the moon are the celestial realm of a fifth element—the quintessence, Aristotle's aether. This element never combines with the other elements and, unlike them, is incorruptible and exists only in the pure state, separately in its own realm in the heavens. Aristotle associated a natural motion with the aether, too, not straight-line motion toward or away from the center, but perfect circles around the center. This seemingly metaphysical doctrine of the perfection of the celestial region is also based on naturalistic observations—heavenly objects appear in fact to be spherical and seem (at least in daily motion) to move in perfect circles around the earth. The enduring and unchanging face of the heavens that we observe from our world of flux and change is related to the unchangeable character of the aether. This dual physics, with separate laws of motion for terrestrial and celestial realms, was consistent with everyday experience and observation and remained intact until the seventeenth century when it was superseded by Newton's laws of motion and universal attraction which postulated a single physics for the whole cosmos.

In addition to the naturally occurring up or down motion of bodies composed of earth, water, fire, and air, nonspontaneous motion observed in the world around us, such as the flight of an arrow, requires explanation. Aristotle envisioned all such motion as forced or violent (as against natural) motion. He proclaimed that such motion always requires an external mover, someone or something to apply an outside force of some sort to cause the motion in question. Moreover, the mover must be in constant contact with the object. In the vast majority of instances Aristotelian movers can be easily identified and the principle apparently confirmed: the horse pulls the cart, the wind blows the sail, and the hand guides the pen. But paradoxical counterexamples exist: the arrow or the javelin in flight after it has lost contact with its mover. Where is the mover in those cases? (Aristotle himself said the medium somehow does the pushing.) In addition, for Aristotle the apparently unmoved motion of animals or plants derives from the faculties of their souls—the animal or vegetable (or, in the case of human beings, the rational) souls they possess.

Except for the puzzling case of projectile motion Aristotle's theory appears to be consistent with at least casual observations of the physical world. Aristotle went beyond these general principles and postulated quantitative relationships among force, velocity, and resistance. His results were not self-evidently implausible. He gave the example of a boat dragged across a beach. Clearly, the boat will not move by itself; an external motive force is required. That force has to be sufficient to overcome the resistance of the friction between boat and sand before any motion can occur; and the speed with which the boat moves thereafter depends on how much force is applied beyond that minimum. The harder the haulers haul, the faster the boat will go; the greater the friction, the slower it will go. In the case of a falling body, the motive force is proportional to the *weight* of the body, so it follows that heavy bodies will fall downwards faster than light bodies (the more earthy matter a body has, the heavier it is, and the more easily it "divides the air" to descend to its natural place). This notion follows from Aristotle's principles and harmonizes with what we observe. For example, a heavy book falls faster than a light sheet of paper. Similarly, the same object falls more slowly in water than in air, and still slower in honey or in molten lead, where it may even float. In these and many other ways, Aristotle's notions hold for what we observe and experience. One can easily understand why his philosophy of nature prevailed for so long.

Another historically significant principle follows from Aristotle's law of motion, the idea that motion must take place in a medium of some appreciable density. In other words, motion in a vacuum is impossible. Motion in a vacuum implies motion without resistance; but if resistance tends toward zero, the velocity of a moving body becomes infinitely large, which implies that a body can move with infinite speed and can thus be at two places at the same time, an apparent absurdity completely inconsistent with all experience. A corollary of Aristotle's rejection of the vacuum was repudiation of atomism, denying the doctrine of empty space through which atoms supposedly moved. For Aristotle space must be completely filled. The power and comprehensiveness of Aristotle's conception of motion overcame the objections that were intermittently leveled against it. It would ultimately take a profound scientific revolution to overthrow Aristotelian views on motion in a medium and to replace them with an alternative doctrine. For two millennia Aristotle's views concerning the stuff of the world, the concept of place, and the principles of motion made great sense and were accordingly held and shared by those who studied natural philosophy in the Greek tradition.

It would be a mistake to overemphasize the physical sciences in analyzing Aristotle's thought, even though they were fundamental to his worldview. Aristotle was tremendously influential and highly skilled as an observational—one can almost say experimental—biologist and taxonomist. (We must remember, however, that the word *biology* did not come into existence until the nineteenth century of our era.) He conducted empirical investigations, carefully observing the development of the chick embryo, for example. Something like a third of his writings concern matters biological. Crucially, the model that Aristotle used to explain the all-important issue of change derives not from physics but from biology. The growth and development of living things provided a model of change for Aristotle with change embodying a process of becoming, of coming-into-being, the "actualization of that which is potential" in things, as in the classic example of the potential oak in the actual acorn. Growth or change merely brings out features that already exist potentially, thus avoiding the Parmenidean paradox of creating something from nothing. Furthermore, for Aristotle, the passing away of one form involves the coming-to-be of another, and therefore the cosmos must be eternal, with cycles of time repeating themselves *ad infinitum.*

In the details of his dealings with living things Aristotle became the pioneer of systematic taxonomy. He ranked life into a grand hierarchy, classifying animals into "bloodless" invertebrates and vertebrates with blood. His identification of three types of "soul" (nutritive, sensitive, and rational), corresponding to vegetable, animal, and the higher cognitive functions of humans, provided a link to anatomy and physiology, or considerations of how the body operates. Aristotle endorsed the concept of spontaneous generation, and he conceived reproduction as males contributing "form" and females only "matter" to the offspring. Over the ages, Aristotle proved as influential in the life sciences as he did in the physical sciences; in particular the later Greco-Roman physician and likewise influential theorist Galen began his work within the basic frame of reference that Aristotle had set down. Theophrastus of Eresus (371–286 BCE), Aristotle's successor as head of the Lyceum in Athens, extended the range of the master's investigations into botany in work that remained a standard source until the eighteenth century.

Aristotle was not a dogmatic philosopher and his word was not taken as gospel. Rather, while his basic tenets were retained, his work provided a springboard for scientific research and for traditions of inquiry that unfolded over the succeeding centuries. Theophrastus directed a trenchant criticism at Aristotle's doctrine of fire as one of the elements. With regard to local motion, by highlighting the phenomenon of acceleration, Strato of Lampsacus, successor to Theophrastus at the Lyceum from 286 to 268 BCE, criticized Aristotle's lack of attention to the speeding up and slowing down of bodies as they begin or end their motion. The Byzantine natural philosopher John Philoponus later added to this ongoing debate over Aristotle's theories of motion, and thinkers in the European Middle Ages intensified the controversies and eventually produced radical revisions of Aristotle's doctrines. This critical tradition evolved over a period of 2,000 years.

Aristotle's writings provided the basis of higher learning in the cultures of late antiquity, Islam, and the European Middle Ages. His cosmos remained at root theological, and, like Plato, he held the heavens to be animate and divine, kept in motion by the Unmoved, or Prime Mover. To this extent Aristotle's philosophy could be harmonized with the theologies of Judaism, Christianity, and Islam, and ultimately theologians of all three faiths bent their efforts to squaring their religious doctrines with Aristotle's teachings. By the same token, many Byzantine, Muslim, and Christian scientists found their inspiration in attempts to understand nature—what they believed to be God's handiwork. With its notions of hierarchy and chains of being, much else in Aristotle resonated with later Christianity and the political interests of ruling political authorities, a circumstance that doubtless also helped insure the long-term success of his natural philosophy.

The intellectual legacy of Aristotle's studies shaped the history of scientific thought in the civilizations that inherited Greek learning. The clarity of his analyses and the cosmological comprehensiveness of his views set the standard for the scientific cultures following the Hellenic Enlightenment. The coincidence that Aristotle and his pupil Alexander the Great died within a year of one another (322 and 323 BCE, respectively) seems emblematic, for in their ways they both transformed the contemporary world. The world that immediately followed their deaths was far different—scientifically and politically—than the one they had inhabited.