The Beginnings of Western Science

The European Scientific Tradition in Philosophical, Religious, and Institutional Context, Prehistory to A.D. 1450

SECOND EDITION

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developed—different categories of healers coming to have somewhat different specialties and functions. And again we find healing intimately mingled with religion and with practices that we would now view as magical. Disease was regarded as the result of invasion of the body by evil spirits (owing to fate, carelessness, sin, or sorcery). Therapy was directed toward elimination of the invading spirit through divination (including the interpretation of astrological omens), sacrifice, prayer, and magical ritual.[33]

This brief sketch of Egyptian and Mesopotamian contributions to mathematics, astronomy, and the healing arts offers us a glimpse of the beginnings of the Western scientific tradition, as well as a background against which to view the Greek achievement. There is no doubt that the Greeks were aware of the work of their Egyptian and Mesopotamian predecessors, and benefited from it. In the chapters that follow, we will see how these products of Egyptian and Mesopotamian thought entered and helped shape Greek natural philosophy.

2 *The Greeks and the Cosmos*

THE WORLD OF HOMER AND HESIOD

Sing to me of the man [Odysseus], Muse, the man of twists and turns
  driven time and again off course, once he had plundered
  the hallowed heights of Troy.
Many cities of men he saw and learned their minds,
  many pains he suffered, heartsick on the open sea,
  fighting to save his life and bring his comrades home.
But he could not save them from disaster, hard as he strove—
  the recklessness of their own ways destroyed them all,
  the blind fools, they devoured the cattle of the Sun
  and the Sungod blotted out the day of their return.
Launch out on his story, Muse, daughter of Zeus,
  start from where you will—sing for our time too.
                                                  By now,
all the survivors, all who avoided headlong death
  were safe at home, escaped the wars and waves.
But one man alone . . .
  his heart set on his wife and his return—Calypso
  the bewitching nymph, the lustrous goddess, held him back,
  deep in her arching caverns, craving him for a husband.
But then, when the wheeling seasons brought the year around,
  that year spun out by the gods when he should reach his home,
Ithaca—though not even there would he be free of trials,
  even among his loved ones—then every god took pity,
  all except Poseidon. He raged on, seething against
  the great Odysseus till he reached his native land.[1]

So begins Homer's *Odyssey*, recounting the return of Odysseus to Ithaca at the conclusion of the Trojan War—alternately thwarted and aided by the gods.[2]

Committed to writing, probably, in the seventh century B.C., the *Odyssey* is a tale of heroic deeds performed in the face of divine intervention and interference. Along with the *Iliad* (also attributed to Homer), it is the closest thing we have to a history of the Greek people before the sixth century. Not history as we moderns would write it, of course, but the two poems do offer an account of historical events and heroic deeds of the past. And they are the best window we've got on the intellectual furniture—the language, learning, and culture—of the ancient Greek mind.

But Homer is not our only source for Greek mythological thought. Hesiod, Homer's rough contemporary, provided a mythological cosmogony in his *Theogony*:

> First came Chasm; then broad-breasted Earth, secure seat for ever of all the immortals who occupy the peak of snowy Olympus. . . . Out of Chasm came Erebos and dark Night, and from Night in turn came Bright Air and Day, whom she bore in shared intimacy with Erebos. Earth bore first of all one equal to herself, starry Heaven . . . and she bore the long Mountains, pleasant haunts of the goddesses, the Nymphs who dwell in mountain glens; and she bore also the undraining Sea and its furious swell.[3]

Gaia (mother earth; fig. 2.1) proceeded to mate with her offspring, Ouranos (father heaven), and from that union issued Oceanus (the river that encircles the world, father of all other rivers), the twelve Titans, and a collection of monsters. Eventually Kronos, one of the Titans, castrated and overthrew his father, Ouranos; Kronos, in turn, was deposed by his son Zeus (fig. 2.2). Zeus obtained the thunderbolt from the Cyclopes and used it to defeat the Titans and establish his own Olympian rule.[4]

We also have short fragments from other early mythographers and many later collections from the Hellenistic period (after 335 B.C.). What strikes one about the world defined by this mythological literature is that it is drenched with the divine. The gods and humans shared a common history. This was a world of anthropomorphic deities interfering in human affairs, using humans as pawns in their own plots and intrigues—acting out of spite, anger, love, lust, benevolence, pleasure, or simple caprice. The gods were also implicated in natural phenomena. Sun and moon were conceived as deities, offspring of Theia and Hyperion. Storms, lightning bolts, winds, and earthquakes were not regarded as inevitable outcomes of impersonal, natural forces, but mighty feats willed by the gods. The result was a capricious world, in which nothing

Fig. 2.1. A shrine to the earth goddess Gaia at Delphi (4th c. B.C.).

could be safely predicted because of the boundless possibilities of divine intervention.

What are we to make of this? Did the ancient Greeks take the stories constituting what we now call "Greek mythology" to be literally true? Did they really believe in divine beings, lodged on Mount Olympus or in some other mysterious place, seducing one another and bedeviling humans who crossed their path? Was there nobody who doubted that storms and earthquakes were a result of divine caprice? We have seen in the previous chapter, in the discussion of preliterate thought, how difficult these questions are.[5] What is clear is that any attempt to measure such beliefs by modern criteria of scientific truth is a sure road to misunderstanding. But perhaps we can learn something by comparing Homeric mythology with modern beliefs outside the scientific realm. When a professional athlete thanks God for victory, does he or she really believe that victory was obtained through supernatural intervention? Or

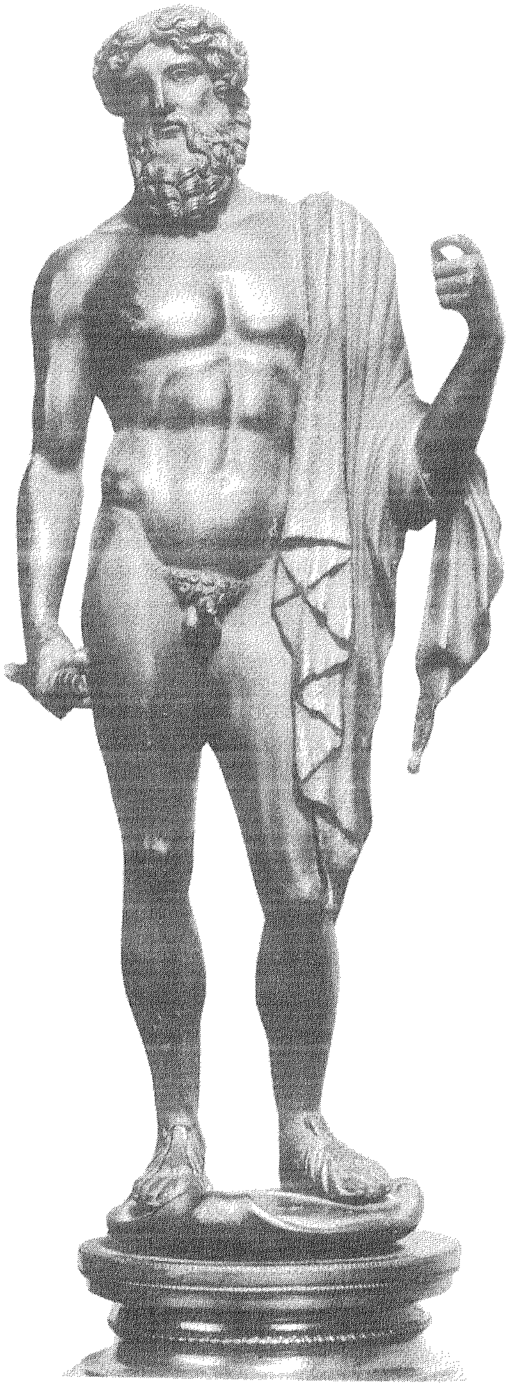


Fig. 2.2. A bronze statue of Zeus. Museo Archeologico, Florence. Alinari/Art Resource N.Y.

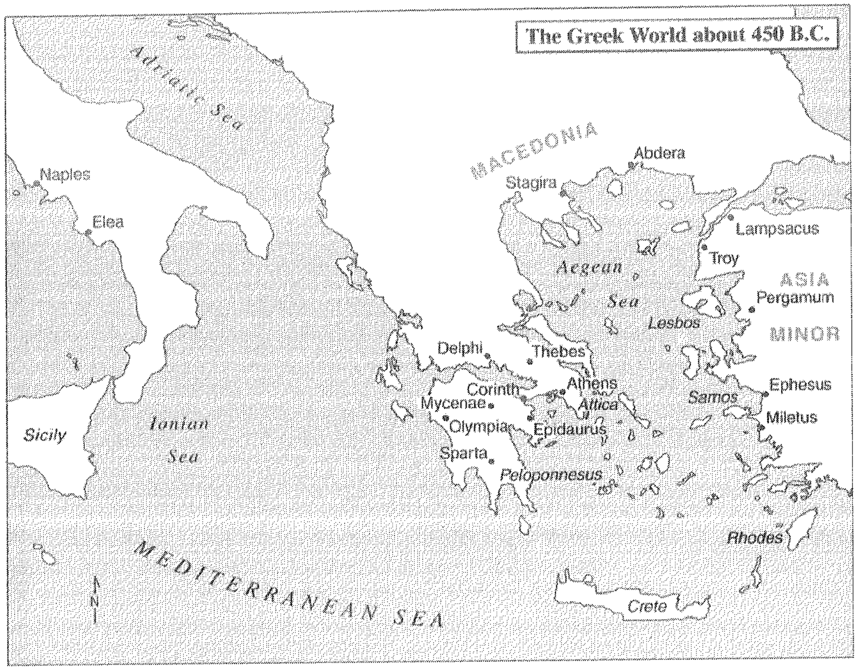
is this simply a case of conventional athlete-talk? At some level, most of the athletes in question would probably expect their claim to be taken seriously. But it has probably never occurred to them that such claims might be asked to survive philosophical or scientific scrutiny. They are not casting about for defensible philosophical or scientific truth, but celebrating victory by expressing conventional, unconsciously assimilated beliefs, widely held in the culture to which they belong. By the same token, although the writings of Homer and Hesiod appear to address questions of causation, we must understand that they were not intended as scientific or philosophical treatises—the very idea of which did not yet exist. Homer and Hesiod—and the bards whose epic poems lie behind theirs—were recording heroic deeds in conventional terms, in order to instruct and entertain; if we treat them as failed philosophers or scientists, we will inevitably misunderstand their achievement.

Yet we must not dismiss these ancient sources too quickly. Homer and Hesiod, after all, are among the few sources at our disposal that reveal anything of archaic Greek thought; and if they do not represent primitive Greek philosophy, they were nonetheless central to Greek education and culture for centuries and cannot have been without influence on the Greek mind. It is abundantly clear that the language and the images people employ affect the reality they perceive. If the content of Homer's and Hesiod's poems was not "believed" in the same way as we believe the content of modern physics or chemistry, the mythology of the Olympian gods, as well as local deities, was nonetheless a central feature of early Greek culture, affecting the way Greeks thought, talked, and behaved.

THE FIRST GREEK PHILOSOPHERS

However, a fresh wind was about to blow from another direction. Early in the sixth century, Greek culture experienced a burst of a radically new kind of discourse—speculation unprecedented in its rationality (*nous* in Greek), its concern for evidence, and its acknowledgment that claims were open to dispute and needed to be defended.[6] Speculations ranged over a broad subject matter, including the cosmos and its origins, the earth and its inhabitants, celestial bodies, striking phenomena such as earthquakes, thunder, and lightning, disease and death, and the nature of human knowledge.

The Greek-speaking people who produced this burst of intellectual activity were distributed geographically over an area that extended well beyond the boundaries of the modern Greek state. Colonization, conquest, and the absorption of invading tribes had created a territory of Greek-speaking people



Map 2.1. The Greek world about 450 B.C.

that extended as far north as Macedonia; east to Asia Minor (modern Turkey), especially the region of Ionia along its Aegean coastline (see map 2.1); and west, across the Adriatic Sea to southern Italy and Sicily. The mingling of peoples and cultures in these territories may help to explain the appearance of philosophical and cosmological thinking in the sixth and fifth centuries.[7]

What were these new modes of thought that we identify as "philosophy"? A small band of thinkers in the sixth century embarked on a serious, critical inquiry into the nature of the world in which they lived—an inquiry that has stretched from their day to ours. They asked about its ingredients, its composition, its operation, and its shape. They inquired whether it is composed of one kind of thing or many. They sought to understand the causes of change, by which things come into being or change character. They contemplated extraordinary natural phenomena, such as earthquakes and eclipses, and sought universal explanations applicable not only to a particular earthquake or eclipse but to earthquakes and eclipses in general. And they began to reflect on the rules of argumentation and proof.

These early philosophers did not merely pose a new set of questions; they also sought new kinds of answers. They did not personify Nature, and the gods

disappeared from their explanations of natural phenomena. Whereas Hesiod regarded earth and sky as divine offspring, for the philosophers Leucippus (fl. 435) and Democritus (fl. 410) the world and its various parts result from mechanical sorting of lifeless atoms in a primeval vortex or whirlpool. To be sure, these philosophical developments did not signal the end of Greek mythology. As late as the fifth century, the historian Herodotus retained much of the old mythology, sprinkling tales of divine intervention through his *Histories*. Poseidon, by his account, used a high tide to flood a swamp the Persians were crossing. And Herodotus regarded an eclipse that coincided with the departure of the Persian army for Greece as a supernatural omen. But the philosophers offered a new and (judging from its subsequent growth) powerful alternative, containing no hint of supernatural intervention. Anaximander (fl. 555) judged eclipses to be the result of blockage of the apertures in rings of celestial fire. According to Heraclitus (fl. 500), the heavenly bodies are bowls filled with fire, and an eclipse occurs when the open side of a bowl turns away from us. These theories of Anaximander and Heraclitus do not seem particularly sophisticated (fifty years after Heraclitus the philosophers Empedocles and Anaxagoras understood that eclipses were simply a case of cosmic shadows), but what is of critical importance is that they exclude the gods. The explanations are entirely naturalistic; eclipses do not reflect personal whim or the arbitrary fancies of the gods, but simply the nature of fiery rings or of celestial bowls and their fiery contents.

The world of the philosophers, in short, was an orderly, predictable world in which things behave according to their natures. The Greek term used to denote this ordered world was *kosmos*, from which we draw our word "cosmology." The capricious world of divine intervention was being pushed aside, making room for order and regularity; *chaos* was yielding to *kosmos*. A clear distinction between the natural and the supernatural was emerging; and there was wide agreement that causes (if they are to be dealt with philosophically) must be sought only in the natures of things. The philosophers who introduced these new ways of thinking were called by Aristotle *physikoi* or *physiologoi*, from their concern with *physis* or nature.

THE MILESIANS AND THE QUESTION OF UNDERLYING REALITY

The philosophical developments described above appear to have emerged first in Ionia. There Greek colonists had established thriving cities, including Ephesus, Miletus, and Pergamum—cities whose prosperity was built on trade and the exploitation of local natural resources. Ionia may, like many frontier societies, have encouraged hard work and self-sufficiency and, in return, offered prosperity and opportunity. It also brought Greeks into contact with the art, religion, and learning of the Near East, with which Ionia had cultural, commercial, diplomatic, and military relations. This, along with the mingling of cultures, growth of literacy within the ruling class, and other causes now beyond our reach led to a burst of creativity in lyric poetry and philosophy.

Later authors, including Aristotle, identify Thales (fl. 585) of Miletus as the earliest of the Ionian philosophers. The surviving fragments (which do not contain any original writings by Thales himself) portray him as a geometer, astronomer, and engineer. He has acquired modern fame for allegedly predicting a solar eclipse in 585, but it is unlikely that Greek astronomical knowledge had developed to the point, in Thales' lifetime, where such a prediction was possible. Other fragments assign him the theory that the earth emerged out of water, on which it now floats like a log—a notion that may be a truer measure of his astronomical and cosmological sophistication. But what is more interesting to us in the present context is the claim (attributed to him by Aristotle two-and-a-half centuries later) that there must be some underlying matter in the universe—water, he believed—out of which everything else is composed and which persists through apparent change: Most of the early philosophers, Aristotle says, conceived that the fundamental, originating stuff that underlies all things is material:

> That of which all things consist, from which they first come and into which, on their destruction, they are ultimately resolved, the substance persisting but changing its qualities—this they say is the element and the origin of all things. . . . Thales, the founder of this school of philosophy, claims that this fundamental stuff is water, which explains why he claimed that the earth floats on water.[8]

This theme of underlying matter or stuff was developed by two younger Milesians, Anaximander (fl. 550) and Anaximenes (fl. 535). The former identified the origin or fundamental stuff of the universe as the *apeiron*, a spacially unlimited and undefined something (and therefore unlike any known substance), out of which the material cosmos emerged.[9] Finally, Anaximenes is reported by Aristotle and Theophrastus to have maintained that the underlying stuff is air, which can be rarefied or condensed to produce the variety of substances found in the world as we know it. This air "differs in its substantial nature by rarity and density. Being made finer it becomes fire, being made thicker it becomes wind, then cloud, then (when thickened still more) water, then earth, then stones; and the rest come into being from these."[10] (This same idea was explored by Newton in the seventeenth century.) It is clear that the Milesian philosophers were monists (for they identify a *single* underlying reality) and materialists.

All of this may seem primitive. And judged by twenty-first-century criteria, it surely is. But comparing the past with the present is a sure recipe for distorting the achievements of the past. It is when we compare the Milesians with their predecessors that their importance becomes apparent. In the first place, our three Milesian philosophers posed a new sort of question, never before (as far as we know) asked in Greek or Middle Eastern culture: what is the material origin of things—the single and simple underlying reality that can take on a variety of forms to produce the diversity of substances that we perceive? This is a search for unity behind diversity and order behind chaos. Second, in the answers offered by these Milesians we find no personification or deification of nature; a conceptual chasm separates their worldview from the mythological world of Homer and Hesiod. The Milesians left the gods out of the story. What they may have thought about the Olympian gods we do not (in most cases) know; but they did not invoke the gods to explain the origin, nature, or cause of things. Third, the Milesians seem to have been aware of the need not simply to report their theories, but also to defend them against critics and competitors. This was the beginning of a tradition of critical assessment, which also continues to the present day.[11]

Milesian speculations about the underlying stuff were the beginning of a quest that has continued from their day to ours. In antiquity, the Milesians were succeeded by various schools of thought. Fifty years later Heraclitus (fl. 500) of Ephesus (an Ionian city not far from Miletus; fig. 2.3) argued for a world without beginning or end, composed ultimately of fire—an "ever-living fire," in a state of continuous transformation between fire in its "kindled" form (which we call "fire" or "flame") and its two other forms: water (fire liquified) and earth (fire soldified). A dynamic balance between these three forms, according to Heraclitus, assures an eternal, stable universe.[12] Heraclitus thus postulates a world of simultaneous stability and change. It was he, according to Plato, who compared this world with the flow of a river and authored the famous maxim that we can never step twice into the same river.[13]

The materialism of the sixth century was extended in the second half of the fifth century by the atomists Leucippus of Miletus (fl. 440) and Democritus of Abdera (fl. 410), who argued that the world consists of an infinity of tiny atoms moving randomly in an infinite void. These atoms, solid corpuscles too small to be seen, come in an infinitude of shapes; by their motions, collisions,

Fig. 2.3. The ruins of ancient Ephesus. SEF/Art Resource N.Y.

and transient configurations, they account for the great diversity of substances and the complex phenomena that we experience. At a cosmic level, the atoms move in huge vortices or whirlpools, out of which worlds (including ours) emerge and into which they again disappear.[14]

The atomists offered ingenious accounts of many other natural phenomena, but we must not allow ourselves to be diverted from the main point. What is important about the atomists is their vision of reality as a lifeless piece of machinery, in which everything that occurs is the necessary outcome of inert, material atoms moving according to their nature. No mind and no divinity intrude into this world. Life itself is reduced to the motions of inert corpuscles. No room exists for purpose or freedom; iron necessity alone rules. This mechanistic worldview would fall out of favor with Plato and Aristotle and their followers. And atomism survived during the Middle Ages principally as an object of abuse, but occasionally as the subject of serious interest.[15] It returned

with a vengeance (and a few novel twists) in the seventeenth century and has been a powerful force in scientific discussions ever since.

Not all who investigated the underlying stuff were monists or materialists. Nor were the gods altogether absent from their explanations.[16] Empedocles of Acragas (fl. 450), a rough contemporary of Leucippus in the second half of the fifth century, identified four elements or "roots" (as he called them) of all material things: fire, air, earth, and water (introduced in mythological garb as Zeus, Hera, Aidoneus, and Nestis). From these four roots, Empedocles wrote, "sprang all things that were and are and shall be, trees and men and women, beasts and birds and water-bred fishes, and the long-lived gods too, most mighty in their prerogatives. For there are these things alone, and running through one another they assume many a shape."[17] But material ingredients alone cannot explain motion and change. Empedocles therefore introduced two additional, *immaterial* principles: love and strife, which induce the four roots to congregate and separate.

Empedocles was not the only ancient philosopher to include immaterial principles among the most fundamental things. The Pythagoreans of the sixth and fifth centuries (concentrated especially in the Greek colonies of southern Italy and known to us not as individuals but as a "school" of thought) seem to have argued, if we interpret them literally, that the ultimate reality is numerical rather than material—not matter, but number. Aristotle reports that in the course of their mathematical studies the Pythagoreans were struck by the power of numbers to account for phenomena such as the musical scale. According to Aristotle, "Since . . . all other things seemed in their whole nature to be modeled after numbers, and numbers seemed to be the first things in the whole of nature, they [the Pythagoreans] supposed the elements of numbers to be the elements of all things, and the whole heaven to be a musical scale and a number."[18] Now this is an obscure passage, and our uncertainty is compounded by the likelihood that Aristotle did not fully understand the Pythagorean teaching and the possibility that, with his own axes to grind, he was not altogether fair to it. Did the Pythagoreans literally believe that material things were constructed out of numbers? Or did they mean only to claim that material things have fundamental numerical properties, which determine the nature of those things? We will never know for certain. A sensible reading of the Pythagorean position is that in some sense numbers came first, and everything else is their offspring; number is in that sense the fundamental reality, and material things derive their properties, and possibly their existence, from number. If we wish to be more cautious, we can affirm at the very least that the Pythagoreans regarded number as a fundamental aspect of reality and mathematics as a basic tool for investigating this reality.

THE QUESTION OF CHANGE

If the most prominent philosophical problem of the sixth century was this question of the origins and fundamental ingredients of the world, a related issue came to dominate the philosophical enterprise in the fifth century. Is change possible, and if so, how? This may seem a ludicrous question to twenty-first-century readers, but with a little effort we may be able to understand its saliency for fifth-century philosophers. In the first place, we need to understand that the question was not addressed to laymen or in the context of the daily activities of laborers, craftsmen, merchants, and the like. It was a logical conundrum, thrown out as a challenge to philosophers: can there be change, motion, and activity in the material world as we experience it if the ingredients of that world are absolutely unchangeable, totally passive stuff? If the fundamental building blocks of the universe simply sit passively in their place, how (as a question of either logic or metaphysics) are motion and other forms of change possible?

The metaphysical approach (which probes the nature and structure of reality at its deepest level) was taken by Heraclitus, who (as we saw in the preceding section) offered a ringing declaration of the reality (indeed, universality) of change—the struggle of opposites—within an overall state of equilibrium or stability.[19] What Heraclitus affirmed, his younger contemporary Parmenides (fl. 480, from the Greek city-state at Elea in southern Italy) denied. Parmenides wrote a long philosophical poem (philosophy had not yet settled on prose as its preferred form of presentation), large sections of which have survived. In it, he adopted the radical position that change—all change—is a logical impossibility. He began by denying, on various logical grounds, the possibility that a thing should pass from nonexistence to existence: for example, if a thing were to come into being, why at one moment rather than another, and by what means? Moreover, this would be getting something from nothing—a logical impossibility. On analogous grounds it is impossible for a thing to undergo change. If A becomes B, either it was already B (that is, it possessed some B-ness) or it was not already B. If A was already B, then no change occurred; if A was not already B, then change would require the acquisition of B-ness from something that did not possess that quality—which brings us back to the impossibility of getting something from nothing. In either case, then, no change occurred.[20]

Parmenides' pupil Zeno (fl. 450) extended and defended this Parmenidean doctrine with a set of proofs against the possibility of one kind of change—motion, or change of place, but presumably applicable to other forms of change

as well. One of these proofs, the "stadium paradox," will illustrate Zeno's approach. It is impossible, Zeno argued, ever to traverse a stadium, because before you cover the whole you must cover the half; and before you cover the half, you must cover the quarter; before the quarter, the eighth; and so on to infinity. To traverse a stadium is therefore to traverse an infinite sequence of halves, and it is impossible to traverse, or even "to come into contact with" (as Aristotle put it in his discussion of the paradox), an infinity of intervals in a finite time. The same argument can be applied to any spatial interval whatsoever—from which it follows that all motion is impossible.[21]

We have no way of knowing whether (or how) Parmenides and Zeno attempted to carry these logical conclusions over into the real world. There is little doubt that they got up in the morning, enjoyed a good breakfast, and made their way to the agora (the public square) for a hard day's philosophizing. But when they reached the agora, did they spend the rest of the day arguing that they were still at home in bed? I doubt it. They knew full well where they were and how long it had taken to get there; but as long as they were wearing their logicians' hats, they were (we may presume) prepared to ponder the logical consequences and range of applicability of what they took to be secure logical premises concerning the possibility of change.

Parmenides' denial of the possibility of change was enormously influential, offering a challenge that generations of philosophers felt compelled to address. Empedocles answered with his theory of four material "roots" or elements, plus love and strife. The elements do not come into being or pass away, and so the fundamental Parmenidean requirement is met. But they do congregate and separate and mix in various proportions, from which it follows that change is also genuine. The atomists Leucippus and Democritus granted that the individual atom is absolutely immutable, so that at the atomic level there is no generation, corruption, or alteration of any kind. However, these immutable atoms are perpetually moving, colliding, and congregating; and through the various motions and configurations of the atoms the endless variety in the world of sense experience is produced. According to the atomists, therefore, stability of the underlying reality (the atoms) underlies change at the sensory level; both are genuine.[22]

THE PROBLEM OF KNOWLEDGE

Poking through these discussions of the underlying reality and the problem of change and stability has been a third basic issue, which early Greek philosophers also addressed—namely, the problem of knowledge (more technically known as epistemology). It is implicit in the quest for the fundamental reality underlying the variety of substances revealed by the senses: if the senses do not reveal what the intellect attests—fundamental stability, for example—then we must abandon the senses as a guide to the truth. Parmenides' radical stance on the question of change had clear-cut epistemological implications: if the senses reveal change, their unreliability would seem to be demonstrated; it follows that truth is to be gained only by the exercise of reason. The atomists, too, had reason to denigrate sense experience. After all, the senses revealed the "secondary" qualities—color, taste, odor, and the tactile qualities—whereas reason taught that only atoms and the void truly exist. In a surviving fragment, Democritus identifies "two forms of knowledge, one genuine, one obscure. To the obscure belong all the following: sight, hearing, smell, taste, touch."[23] The fragment breaks off before the idea is completed, but we may assume that in Democritus's judgment genuine knowledge is rational knowledge.

If the early philosophers were inclined to favor reason over sense, this tendency was neither universal nor without qualification. Empedocles defended the senses against the attack of Parmenides. The senses may not be perfect, he argued, but they are useful guides if employed with discrimination. "But come, consider with all thy powers how each thing is manifest," he wrote, "neither holding sight in greater trust as compared with hearing, nor loud-sounding hearing above the clear evidence of thy tongue, nor withholding thy trust from any of the other limbs, wheresoever there is a path for understanding." And Anaxagoras (fl. 450) of Clazomenae (another Ionian coastal city) argued in a brief fragment that the senses offer "a glimpse of the obscure."[24]

One of the benefits gained from Greek epistemological concerns (from Greek rationalism in particular) was that they directed attention to the rules of reasoning, argumentation, and theory assessment. Formal logic would be the creation of Aristotle; but his sixth- and fifth-century predecessors became increasingly aware of the need to test the soundness of an argument and to assess the grounds on which a theory rested. The sophistication with which Parmenides and Zeno could argue—their sensitivity, for example, to the rules of inference and the criteria of proof—demonstrates how far Greek philosophy had come in a century and a half.

PLATO'S WORLD OF FORMS

The death of Socrates in 399 B.C., coming as it did around the turn of the century (not on their calendar, of course, but on ours), has made it a convenient point of demarcation in the history of Greek philosophy. Thus Socrates' predecessors of the sixth and fifth centuries (the philosophers who have occupied us until now in this chapter) are commonly called the "pre-Socratic philosophers." But Socrates' prominence is more than an accident of the calendar, for Socrates represents a shift in emphasis within Greek philosophy, away from the cosmological concerns of the sixth and fifth centuries toward political and ethical matters. Nonetheless, the shift was not so dramatic as to preclude continuing attention to the major problems of pre-Socratic philosophy. We find both the new and the old in the work of Socrates' younger friend and disciple, Plato (fig. 2.4).

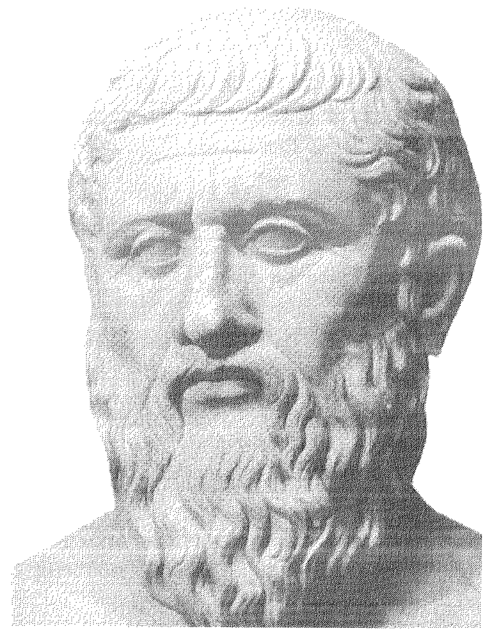


Fig. 2.4. Plato (1st c. A.D. copy). Museo Vaticano, Vatican City. Alinari/Art Resource N.Y.

Plato (427–348/47) was born into a distinguished Athenian family, active in affairs of state; he was undoubtedly a close observer of the political events that led up to Socrates' execution. After Socrates' death, Plato left Athens and visited Italy and Sicily, where he seems to have come into contact with Pythagorean philosophers. In 388 Plato returned to Athens and founded a school of his own, the Academy, where young men could pursue advanced studies (see fig. 4.1). Plato's literary output appears to have consisted almost entirely of dialogues, the majority of which have survived. We will find it necessary to be highly selective in our examination of Plato's philosophy; let us begin with his quest for the underlying reality.[25]

In a passage in one of his dialogues, the *Republic*, Plato reflected on the relationship between the actual tables constructed by a carpenter and the idea or definition of a table in the carpenter's mind. The carpenter replicates the mental idea as closely as possible in each table he makes, but always imperfectly. No two manufactured tables are alike down to the smallest detail, and limitations in the material (a knot here, a warped board there) ensure that none will fully measure up to the ideal.

Now, Plato argued, there is a divine craftsman who bears the same relationship to the cosmos as the carpenter bears to his tables. The divine craftsman (the Demiurge) constructed the cosmos according to an idea or plan, so that the cosmos and everything in it are replicas of eternal ideas or forms—but always imperfect replicas because of limitations inherent in the materials available to the Demiurge. In short, there are two realms: a realm of forms or ideas, containing the perfect form of everything; and the material realm in which these forms or ideas are imperfectly replicated.

Plato's notion of two distinct realms will seem strange to many people, and we must therefore stress several points of importance. The forms are incorporeal, intangible, and insensible; they have always existed, sharing the property of eternality with the Demiurge; and they are absolutely changeless. They include the form, the perfect idea, of everything in the material world. One does not speak of their location, since they are incorporeal and therefore not spatial. Although incorporeal and imperceptible by the senses, they objectively exist; indeed, true reality (reality in its fullness) is located only in the world of forms. The sensible, corporeal world, by contrast, is imperfect and transitory. It is less real in the sense that the corporeal object is a replica of, and therefore dependent for its existence upon, the form. The form has primary existence, its corporeal replica secondary existence.

Plato illustrated this conception of reality in his famous "allegory of the cave," found in book VII of the *Republic*. Men are imprisoned within a deep cave, chained so as to be incapable of moving their heads. Behind them is a wall, and beyond that a fire. People walk back and forth behind the wall, holding above it various objects, including statues of humans and animals; the objects cast shadows on the wall that is visible to the prisoners. The prisoners see only the shadows cast by these objects; and, having lived in the cave from childhood, they no longer recall any other reality. They do not suspect that these shadows are but imperfect images of objects that they cannot see; and consequently they mistake the shadows for the real.

So it is with all of us, says Plato. We are souls imprisoned in bodies. The shadows of the allegory represent the world of sense experience. The soul, peering out from its prison, is able to perceive only these flickering shadows, and the ignorant claim that this is all there is to reality. However, there do exist

the statues and other objects of which the shadows are feeble representations and also the humans and animals of which the statues are imperfect replicas. To gain access to these higher realities, we must escape the bondage of sense experience and climb out of the cave, until we find ourselves able, finally, to gaze on the eternal realities, thereby entering the realm of true knowledge.[26]

What are the implications of these views for the concerns of the pre-Socratic philosophers? First, Plato equated his forms with the underlying reality, while assigning derivative or secondary existence to the corporeal world of sensible things. Second, Plato has made room for both change and stability by assigning each to a different level of reality: the corporeal realm is the scene of imperfection and change, while the realm of forms is characterized by eternal, changeless perfection. Both change and stability are therefore genuine; each characterizes something; but changelessness belongs to the forms and thus shares their fuller reality.

Third, as we have seen, Plato addressed epistemological questions, placing observation and true knowledge (or understanding) in opposition. Far from leading upward to knowledge or understanding, the senses are chains that tie us down; the route to knowledge is through philosophical reflection. This is explicit in the *Phaedo*, where Plato maintains the uselessness of the senses for the acquisition of truth and points out that when the soul attempts to employ them it is inevitably deceived.

Now the short account of Plato's epistemology frequently ends here; but there are important qualifications that it would be a serious mistake to omit. Plato did not, in fact, dismiss the senses altogether, as Parmenides had done and as the passage from the *Phaedo* might suggest Plato did. Sense experience, in Plato's view, served various useful functions. First, sense experience may provide wholesome recreation. Second, observation of certain sensible objects (especially those with geometrical properties) may serve to direct the soul toward nobler objects in the realm of forms. Plato used this argument as justification for the pursuit of astronomy. Third, Plato argued (in his theory of reminiscence) that sense experience may actually stir the memory and remind the soul of forms that it knew in a prior existence, thus stimulating a process of recollection that will lead to actual knowledge of the forms.

Finally, although Plato firmly believed that knowledge of the eternal forms (the highest, and perhaps the only true, form of knowledge) is obtainable only through the exercise of reason, the changeable realm of matter is also an acceptable object of study. Such studies serve the purpose of supplying examples of the operation of reason in the cosmos. If this is what interests us (as it sometimes did Plato), the best method of exploring it is surely to observe it. The legitimacy and utility of sense experience are clearly implied in the *Republic*, where Plato acknowledged that a prisoner emerging from the cave first employs his sense of sight to apprehend living creatures, the stars, and finally the most noble of visible (material) things, the sun. But if he aspires to apprehend "the essential reality," he must proceed "through the discourse of reason unaided by any of the senses." Both reason and sense are thus instruments worth having; which one we employ on a particular occasion will depend on the object of study.[27]

There is another way of expressing all of this, which may shed light on Plato's achievement. When Plato assigned reality to the forms, he was, in fact, identifying reality with the properties that classes of things have in common. The bearer of true reality is not (for example) this dog with the droopy left ear or that one with the menacing bark, but the idealized form of a dog shared (imperfectly, to be sure) by every individual dog—those characteristics by virtue of which we are able to classify all of them as dogs. Therefore, to gain true knowledge, we must set aside all characteristics peculiar to things as individuals and seek the shared characteristics that define them into classes. Now stated in this modest fashion, Plato's view has a distinctly modern ring. Idealization is a prominent feature of a great deal of modern science; we develop models or laws that overlook the incidental in favor of the essential. However, Plato went beyond this, maintaining not merely that true reality is to be found in the common properties of classes of things, but also that this common property (the idea or form) has objective, independent, and indeed prior existence.

PLATO'S COSMOLOGY

The doctrines that we have been considering—Plato's response to the pre-Socratics, found in his *Republic*, *Phaedo*, and various other dialogues—represent only a small portion of his total philosophy. Plato also wrote a dialogue, the *Timaeus*, that reveals his interest in the world of nature. Here we find his views on astronomy, cosmology, light and color, the elements, and human physiology. Since the *Timaeus* was the only Platonic dialogue to survive through the Middle Ages in more than fragmentary form, it represents one of the principal channels of continuing Platonic influence. It is important for our purposes because it provided the early Middle Ages (before the twelfth century) with its most coherent natural philosophy.

Plato referred to the contents of the *Timaeus* as a "likely story," and this has misled some readers to view it as a myth in which Plato himself placed no

stock. In fact, Plato stated quite clearly that this was the best account possible, that anything better than a likely account was precluded by the subject matter. Certainty is attainable only when we give an account of the eternal and unchanging forms; when we describe the imperfect and changeable objects in the material world, our description will inevitably share in the imperfection and changeability of its subject and will therefore be no more than "likely."

What do we find in the *Timaeus*? One of its most striking characteristics is Plato's vehement opposition to certain features of pre-Socratic thought. The *physikoi* had deprived the world of divinity; in the process, they had also deprived it of plan and purpose. According to these philosophers, things behave according to their inherent natures, and this alone accounts for the order and regularity of the cosmos. Order, then, is intrinsic, rather than extrinsic; it is not imposed by an outside agent but arises from within.

Now Plato found such an opinion not only foolish but dangerous. He had no intention of restoring the gods of Mount Olympus, who interfered in the day-to-day operation of the universe, but he was convinced that the order and rationality of the cosmos could be explained only as the imposition of an outside mind. If the *physikoi* found the source of order in *physis* (nature), he would locate it in *psyche* (mind).[28]

Plato depicted the cosmos as the handiwork of a divine craftsman, the Demiurge. According to Plato, the Demiurge is a benevolent craftsman, a rational god (indeed, the very personification of reason) who struggled against the limitations inherent in the materials at his disposal in order to produce a cosmos as good, beautiful, and intellectually satisfying as possible. The Demiurge took a primitive chaos filled with the unformed material out of which the cosmos would be constructed and imposed order according to a rational plan. This was not creation of the cosmos from nothing, as in the Judeo-Christian account of creation, for the raw materials were already present and contained properties over which the Demiurge had no control; nor was the Demiurge omnipotent, for he was constrained and limited by the available materials. Nevertheless, Plato clearly intended to portray the Demiurge as a supernatural being, distinct from, and outside of, the cosmos that he constructed. Whether Plato meant his readers to take the Demiurge literally is another matter, much debated and perhaps incapable of ever being resolved. What is not open to dispute is Plato's wish to declare that the cosmos is the product of reason and planning, that the order in the cosmos is rational order, imposed on recalcitrant materials from outside.

Besides being a rational craftsman, the Demiurge is a mathematician, for he constructed the cosmos on geometrical principles. Plato's account borrowed

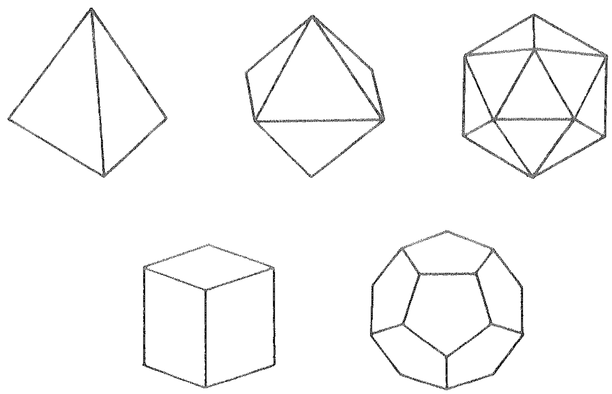


Fig. 2.5. The five Platonic solids: tetrahedron, octahedron, icosahedron, cube, and dodecahedron. Courtesy of J. V. Field.

the four roots or elements of Empedocles: earth, water, air, and fire. But (probably under Pythagorean influence) he reduced them to mathematical ingredients or components. It was already known in Plato's day that there are five, and only five, regular geometrical solids (symmetrical solid figures formed of plane surfaces, all identical); these are the tetrahedron (four equilateral triangles), the cube (six squares), the octahedron (eight equilateral triangles), the dodecahedron (twelve pentagons), and the icosahedron (twenty equilateral triangles). (See fig. 2.5.) Plato made these the basis of a "geometrical atomism"—associating each of the elements with one of the geometrical solids. Fire is the tetrahedron (the smallest, sharpest, and most mobile of the regular solids), air is the octahedron, water the icosahedron, and earth the cube (the most stable of the regular solids). Plato also found a function for the docedahedron (the regular solid closest to the sphere) by identifying it with the cosmos as a whole. This was not the end of Plato's geometrical analysis, for he reduced each of the three-dimensional geometrical figures representing the elements into its two-dimensional components, as we will see just below.[29]

Three features of this scheme deserve discussion. First, it accounts for change and diversity in the same way as does Empedocles' theory: the elements can mix in various proportions to produce variety in the material world. Second, it allows for transmutation of the three elements that are composed of equilateral triangles (the tetrahedron, octahedron, and icosahedron), one to another, thus further accounting for change. For example, a single corpuscle of water (the icosahedron) can be dissolved into its twenty constituent equilateral

triangles, which can then recombine into, say, two corpuscles of air (the octahedron) and one of fire (the tetrahedron). Only earth, which is composed of squares (and the square divided diagonally does not yield an equilateral triangle), is excluded from this process of transmutation. Third, Plato's geometrical corpuscles represent a significant step toward the mathematization of nature. Indeed, it is important for us to see just how large a step it is. Plato's elements are not material substance shaped as a square, tetrahedron, and so forth; in such a scheme matter would still be acknowledged as the fundamental stuff. For Plato, the shape—the geometrical figure—is all there is. The geometrical atoms are nothing more than the regular solids, which are reducible without residue to plane geometrical figures. Water, air, and fire are not *triangular*; they are (in the final analysis) nothing more than *triangles*, appropriately arranged. The Pythagorean program of reducing everything to mathematical first principles has been fulfilled.

Plato proceeded to describe many features of the cosmos; let us glance at a few of them. He demonstrated a sophisticated command of cosmology and astronomy. He proposed a spherical earth, surrounded by the spherical envelope of the heavens. He defined various circles on the celestial sphere, marking the paths of the sun, moon, and other planets. He understood that the sun moves around the celestial sphere once a year on a circle (which we call the ecliptic) tilted in relation to the celestial equator (see fig. 2.6). He knew that the moon makes a monthly circuit of approximately the same path. He knew that Mercury, Venus, Mars, Jupiter, and Saturn do the same, each at its own pace and with occasional reversals, and that Mercury and Venus never stray far from the sun. He even knew that the overall motion of the planetary bodies (if we combine their slow motion around the ecliptic with the daily rotation of the celestial sphere) is a spiral. And what is perhaps most important of all, Plato seems to have understood that the irregularities of planetary motion can be explained by the compounding of uniform circular motions.[30]

When Plato descended from the cosmos to the human frame, he offered an account of respiration, digestion, emotion, and sensation. He had a theory of sight, for example, that supposed that visual fire issues from the eye, interacting with external light to create a visual pathway that could transmit motions from the visible object to the observer's soul. The *Timaeus* even offered a theory of disease and outlined a regimen that was to ensure health.

It was an admirable cosmos that Plato portrayed. What were its most prominent features? From triangles and regular solids the Demiurge fashioned a final product of the utmost beauty and rationality. And the cosmos, if rational, is necessarily a living creature. The Demiurge, we read in the *Timaeus*, "wishing

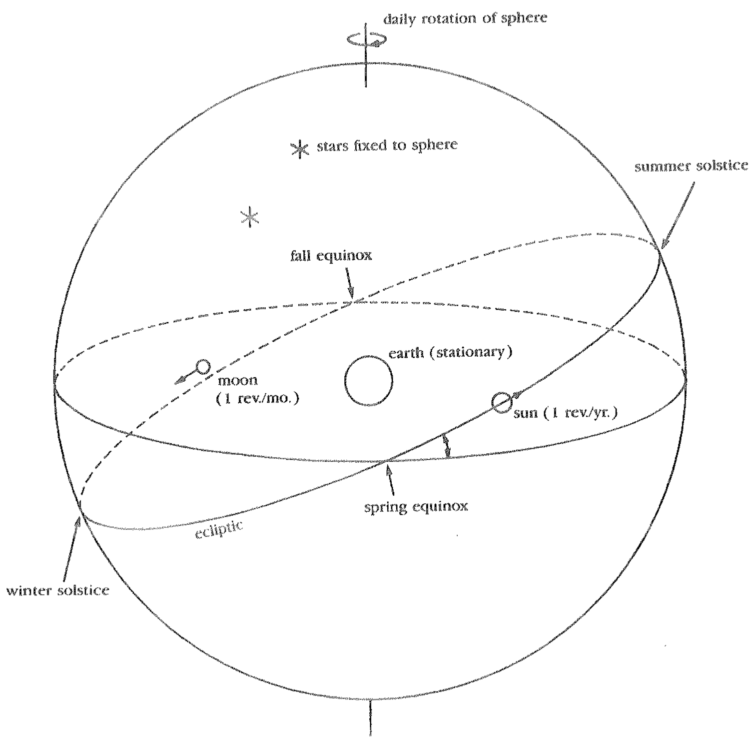


Fig. 2.6. The celestial sphere according to Plato.

to make the world most nearly like that intelligible thing which is best and in every way complete, fashioned it as a single visible living creature." But a living creature must possess a soul; and so in the center of the cosmos the Demiurge "set a soul and caused it to extend throughout the whole and further wrapped its body round with soul on the outside; and so he established one world alone, round and revolving in a circle, solitary but able by reason of its excellence to bear itself company, needing no other acquaintance or friend but sufficient to itself." The world soul is ultimately responsible for all motions in the cosmos, just as the human soul is responsible for the motions of the human body. We see here the origins of the strong animistic strain that was to remain an important feature of the Platonic tradition. Repelled by the lifeless necessity of the atomistic world, Plato has described an animated cosmos, permeated by rationality, replete with purpose and design.[31]

Nor is deity absent. We have the Demiurge, of course; but in addition Plato assigned divinity to the world soul and considered the planets and the fixed stars to be a host of celestial gods. However, unlike the gods of traditional

Greek religion, Plato's deities never interrupt the course of nature. Quite the contrary, it is the very steadfastness of the gods that, in Plato's view, guarantees the regularity of nature; the sun, moon, and other planets must move with some combination of uniform circular motions precisely because such motion is most perfect and rational, and consequently the only kind of motion conceivable for a divine being. Thus Plato's reintroduction of divinity does not represent a return to the unpredictability of the Homeric world. Quite the contrary, the function of divinity for Plato was to undergird and account for the order and rationality of the cosmos. Plato restored the gods in order to account for precisely those features of the cosmos that, in the view of the *physikoi*, required the banishing of the gods.[32]

THE ACHIEVEMENT OF EARLY GREEK PHILOSOPHY

If we survey early Greek philosophy with a modern scientific eye, certain pieces of it look familiar. The pre-Socratic inquiry into the shape and arrangement of the cosmos, its origin, and its fundamental ingredients reminds us of questions still investigated in modern astrophysics, cosmology, and particle physics. However, other pieces of early philosophy look considerably more foreign. Working scientists today do not inquire whether change is logically possible or where true reality is to be found; and it would be a considerable feat to turn up, say, a physicist or chemist who worries with any regularity about how to balance the respective claims of reason and observation. These matters are no longer talked about by scientists. Does it follow that such questions were a waste of time and that the early philosophers who devoted their lives to them were misguided or intellectually deficient?

This question needs to be handled with some delicacy. Surely the fact that the *physikoi* were concerned about some matters no longer of interest is no indictment of their enterprise; in the course of any intellectual endeavor some problems get resolved, while others go out of fashion. But the objection may go deeper than that: Are there issues that are intrinsically inappropriate or illegitimate, questions that were futile (and ought to have been recognized as such) from the beginning? And did Plato and the *physikoi* waste time and energy on any of these? Perhaps we can answer in this way. Themes such as the identity of the ultimate reality, the distinction between natural and supernatural, the source of order in the universe, the nature of change, and the foundations of knowledge are quite different from the explanation of arcane experimental data (say, a chemical reaction, a physiological process, or a meteorological event) that now occupy most scientists; but to be different is not to be useless or insignificant. At least until Isaac Newton, these larger themes demanded as much attention from the student of nature as did the problems that now fill up a university course in one of the sciences. Such questions were interesting and essential precisely because they were part of the effort to create conceptual foundations and vocabulary for investigating the world; and it is often the fate of foundational questions to seem pointless to later generations who take the foundations for granted. Today, for example, we may find the distinction between the natural and supernatural obvious; but until the distinction was carefully drawn, the investigation of nature could not properly begin.

Thus the early philosophers began at the only possible place: the beginning. They created a conception of nature that has served as the foundation of scientific belief and investigation in the intervening centuries—the conception of nature presupposed, more or less, by modern science. In the meantime many of the questions they asked have been resolved—often with rough-and-ready solutions, rather than definitive answers, but resolved sufficiently to slip from the forefront of scientific attention. As they have sunk from view, their place has been taken by a collection of much narrower investigations. If we would understand the scientific enterprise in all of its richness and complexity, we must see that its two parts—the foundation and the superstructure—are complementary and reciprocal. Modern laboratory investigation occurs within a broad conceptual framework and cannot even begin without expectations (created by predecessors) about nature or the underlying reality; in turn, the conclusions of laboratory research reflect back on these most fundamental notions, forcing refinement and (occasionally) revision. The historian's task is to appreciate the enterprise in all of its diversity. If the garden of the *physikoi* is situated at the beginning of the road to modern science, then the historian of science may profitably dally in its shady corners before embarking on his journey.

3 ❁ *Aristotle's Philosophy of Nature*

LIFE AND WORKS

Aristotle (fig. 3.1) was born in 384 B.C. in the northern Greek town of Stagira, into a privileged family. His father was personal physician to the Macedonian king, Amyntas II (grandfather of Alexander the Great). Aristotle had the advantage of an exceptional education: at age seventeen, he was sent to Athens to study with Plato. He remained in Athens as a member of Plato's Academy for twenty years, until Plato's death about 347. Aristotle then spent several years in travel and study, crossing the Aegean Sea to Asia Minor and its coastal islands. During this period he undertook biological studies, and he encountered Theophrastus (from the island of Lesbos), who was to become his pupil and lifetime colleague. He returned to Macedonia in 342 to become the tutor of the young Alexander (later "the Great"). In 335, when Athens fell under Macedonian rule, Aristotle returned to the city and began to teach in the Lyceum, a public garden frequented by teachers. He remained there, establishing an informal school, until shortly before his death in 322.[1]

In the course of his long career as student and teacher, Aristotle systematically and comprehensively addressed the major philosophical issues of his day. He is credited with more than 150 treatises, approximately 30 of which have come down to us. The surviving works appear to consist mainly of lecture notes or unfinished treatises not intended for wide circulation; whatever their exact origin, they were obviously directed to other philosophers, including advanced students. In modern translation, they occupy well over a foot of bookshelf, and they present a philosophical system overwhelming in power and scope. It is out of the question for us to survey the whole of Aristotle's philosophy, and we must be content with examining the fundamentals of his philosophy of nature—beginning with his response to positions taken by the pre-Socratics and Plato.[2]

Fig. 3.1. Aristotle. Museo Nazionale, Rome. Alinari/Art Resource N.Y.

METAPHYSICS AND EPISTEMOLOGY

Through his long association with Plato, Aristotle had, of course, become thoroughly versed in Plato's theory of forms. Plato had drastically diminished (without totally rejecting) the reality of the material world observed by the senses. Reality in its perfect fullness, Plato argued, is found only in the eternal forms, which are dependent on nothing else for their existence. The objects that make up the sensible world, by contrast, derive their characteristics and their very being from the forms; it follows that sensible objects exist only derivatively or dependently.

Aristotle refused to accept this diminished, dependent status that Plato assigned to sensible objects. They must exist fully and independently, for in Aristotle's view they were what make up the real world. Moreover, the traits that give an individual object its character do not, Aristotle argued, have a prior and separate existence in a world of forms, but belong to the object itself. There is no perfect form of a dog, for example, existing independently in the world of forms and replicated imperfectly in individual dogs, imparting to them their attributes. For Aristotle, there were just individual dogs. These dogs certainly shared a set of attributes—for otherwise we would not be entitled to call them "dogs"—but these attributes exist in, and belong to, individual dogs.

Perhaps this way of viewing the world has a familiar ring. Making individual sensible objects the primary realities ("substances," Aristotle called them) will seem like good common sense to most readers of this book, and probably struck Aristotle's contemporaries the same way. But if it makes good common sense, can it also be good philosophy? That is, can it deal successfully, or at least plausibly, with the difficult philosophical issues raised by the pre-Socratics and Plato—the nature of the fundamental reality, epistemological concerns, and the problem of change and stability? Let us take up these problems one by one.[3]

The decision to locate reality in sensible, corporeal objects does not yet tell us very much about reality—only that we should look for it in the sensible world. Already in Aristotle's day, any philosopher would demand to know more: one thing he would demand to know was whether the corporeal materials of daily experience (wood, water, air, stone, metal, flesh, etc.) are themselves the fundamental, irreducible constituents of things, or whether they are composites of still more fundamental stuff. Aristotle addressed this question by drawing a distinction between properties and their subjects. He maintained (as most of us would) that a property has to be the property *of* something; we call that something its "subject." To be a property is to belong to a subject; properties cannot exist independently.

Individual corporeal objects, then, have both properties (color, weight, texture, and the like) and something other than properties to serve as their subject. These two roles are played by "form" and "matter," respectively. Corporeal objects are "composites" of form and matter—form consisting of the properties that make the thing what it is, matter serving as the subject or substratum for the form. A white rock, for example, is white, hard, heavy, and so forth, by virtue of its form; but matter must also be present, to serve as subject for the form, and this matter brings no properties of its own to its union with form.[4] (Aristotle's doctrine will be further discussed in chap. 12, below, in connection with medieval attempts to clarify and extend it.)

We can never, in actuality, separate form and matter; they are presented to us only as a unitary composite. If they were separable, we should be able to put the properties (no longer the properties *of* anything) in one pile, the matter (absolutely propertyless) in another—an obvious impossibility. But if form and matter can never be separated, is it not meaningless to speak of them as the real constituents of things? Isn't this a purely logical distinction, existing in our minds, but not in the external world? Surely not for Aristotle, and perhaps not for us; most of us would think twice before denying the real existence of cold or red, although we can never collect a bucket of either one.

In short, Aristotle once again surprises us by using commonsense notions to build a persuasive philosophical edifice.

Aristotle's claim that the primary realities are concrete individuals surely has epistemological implications, since true knowledge must be knowledge of truly real things. By this criterion, Plato's attention was naturally directed toward the eternal forms, knowable through reason or philosophical reflection. Aristotle's metaphysics of concrete individuals, by contrast, directed his quest for knowledge toward the material world of individuals, of nature, and of change—a world encountered through the senses.

Aristotle's epistemology is complex and sophisticated. It must suffice here to indicate that the process of acquiring knowledge begins with sense experience. From repeated sense experience follows memory; and from memory, by a process of "intuition" or insight, the experienced investigator is able to discern the universal features of things. By the repeated observation of dogs, for example, an experienced dog breeder comes to know what a dog really is; that is, he comes to understand the form or definition of a dog, the crucial traits without which an animal cannot be a dog. Note that Aristotle, no less than Plato, was determined to grasp the universal traits or properties of things; but, unlike his teacher, Aristotle argued that one must start with the individual material thing. Once we grasp the universal properties or definition, we can put it to use as the premise of deductive demonstrations.[5]

Knowledge is thus gained by a process that begins with experience (a term broad enough, in some contexts, to include common opinion or the reports of distant observers). In that sense knowledge is empirical; nothing can be known apart from such experience. But what we learn by this "inductive" process does not acquire the status of true knowledge until put into deductive form; the end product is a deductive demonstration (nicely illustrated in a Euclidean proof) beginning from universal definitions as premises. Although Aristotle discussed both the inductive and deductive phases (the latter far more than the former) in the acquisition of knowledge, he stopped considerably short of later methodologists, especially in the analysis of induction.

This is the theory of knowledge outlined by Aristotle in the abstract. Is it also the method actually employed in Aristotle's own scientific investigations? Probably not—with perhaps an occasional exception. Like modern scientists, Aristotle did not proceed by following a methodological recipe book, but rather by rough and ready methods, familiar procedures that had proved themselves in practice. Somebody has defined science as "doing your damnedest, no holds barred"; when it came (for example) to his extensive biological researches, this is exactly what Aristotle did. It is not a surprise, and certainly no character defect, that Aristotle should, in the course of thinking about the nature and the foundations of knowledge, formulate a theoretical scheme (an epistemology) not perfectly consistent with his own scientific practice.[6]

NATURE AND CHANGE

The problem of change had become a celebrated philosophical issue (within the quite small community of philosophers) in the fifth century B.C. In the fourth century, Plato had dealt with it by restricting change to the imperfect material replica of the changeless world of forms. For Aristotle, a distinguished naturalist who was philosophically committed to the full reality of the changeable individuals that make up the sensible world, the problem of change was a most pressing one.[7]

Aristotle's starting point was the commonsense assumption that change is genuine. But this does not, by itself, get us very far; it remains to be demonstrated that the idea of change can withstand philosophical scrutiny; it must also be shown how change can be explained. Aristotle had various weapons in his arsenal by which to achieve these ends. The first was his doctrine of form and matter. If every object is constituted of form and matter, then Aristotle could make room for both change and stability by arguing that when an object undergoes change, its form changes (by a process of replacement, the new form replacing the old one) while its matter remains unchanged. Aristotle went on to argue that change in form takes place between a pair of opposites or contraries, one of which is the form to be achieved, the other its privation or absence. When the dry becomes wet, or the cold becomes hot, this is change from privation (dry or cold) to the intended form (wet or hot). Change, for Aristotle, is thus never random, but confined to the narrow corridor connecting pairs of contrary qualities; order is thus discernible even in the midst of change.

A determined Parmenidean might protest that to this point the analysis does nothing to escape Parmenides' objection to all change on the ground that inevitably it calls for the emergence of something out of nothing. Aristotle's reply is found in his doctrine of potentiality and actuality. Aristotle would undoubtedly have granted that if the only two possibilities are being and nonbeing—that is, if things either exist or do not exist—then the transition from non-hot to hot would indeed involve passage from nonbeing to being (the nonexistence of hot to the existence of hot) and would thus be vulnerable to Parmenides' objection. But Aristotle believed that the objection could be successfully circumvented by supposing that there are three categories associated with being instead of two: not just being and nonbeing, but (1) nonbeing, (2) potential being, and (3) actual being. If such is the state of things, then change can occur between potential being and actual being without nonbeing ever entering the picture. What Aristotle has in mind is perhaps most easily illustrated by examples from the biological realm. An acorn is potentially, but not actually, an oak tree. In becoming an oak tree, it becomes actually what it originally was only potentially. The change thus involves passage from potentiality to actuality—not from nonbeing to being, but from one kind or degree of being to another. Or for a pair of nonbiological examples, a heavy body held above the earth falls in order to fulfill its potential of being situated with other heavy things about the center of the universe. And a sculptor, with mallet and hammer, reveals in actuality a shape that existed potentially within the original block of marble.

If these arguments allow us to escape the logical dilemmas associated with the idea of change, and therefore to believe in its possibility, they do not yet tell us anything about the cause of change. Why should an acorn move from the status of potential oak tree to that of actual oak tree, or an object change from black to white, rather than remaining in its original state? Aristotle answered with an intricate, subtle, and not always consistent, theory of nature and causation. Given these difficulties, we will spare ourselves the pain of an exhaustive account and treat ourselves to the short version.

The world we inhabit is an orderly one, in which things generally behave in predictable ways, Aristotle argued, because every natural object has a "nature"—an attribute (associated primarily with form) that makes the object behave in its customary fashion, provided no insurmountable obstacle intervenes—or, as a modern commentator has put it, "that within a thing which determines basically what that thing does when it is being itself." For Aristotle, a brilliant zoologist, the growth and development of biological organisms were easily explained by the activity of such an inner driving force. An acorn becomes an oak tree because its nature is to do so. But the theory was applicable beyond biological growth and, indeed, beyond the biological realm altogether. Dogs bark, rocks fall, and marble yields to the hammer and chisel of the sculptor because of their respective natures. Ultimately, Aristotle argued, all change and motion in the universe can be traced back to the natures of things. For the natural philosopher, who by definition is interested in change and things capable of undergoing change, these natures are the central object of study.[8]

To this general statement of Aristotle's theory of "nature," we need to add a qualification—namely, that an artificially produced object is a special case,

for such an object possesses no nature other than the natures of its ingredients. If a chariot is constructed of wood and iron, the nature of wood and nature of iron do not yield to a composite "nature of a chariot." By contrast, in the organic world the natures of the organs and tissues that make up an organism yield to the nature of the organism as a whole. The nature of the human body is not the sum of the natures of its various tissues and organs, but a unique nature characteristic of that living human as an organic whole.

With this theory of nature in mind, we can understand a feature of Aristotle's scientific practice that has puzzled and distressed modern commentators and critics—namely, the absence from his work of anything resembling controlled experimentation. Unfortunately, such criticism overlooks Aristotle's aims, which drastically limited his methodological options. If, as Aristotle believed, the nature of a thing is to be discovered through the behavior of that thing in its natural, unfettered state, then artificial constraints will merely interfere and corrupt.[9] If, despite interference, the object behaves in its customary fashion, we have troubled ourselves for no purpose. If we set up conditions that prevent the nature of an object from revealing itself, all we have learned is that it can be interfered with to the point of remaining concealed. Contrived experimentation violates, rather than reveals, the natures of things. Aristotle's scientific practice is not to be explained, therefore, as a result of stupidity or deficiency on his part—failure to perceive an obvious procedural improvement—but as a method compatible with the world as he perceived it and suited to the questions that interested him. Experimental science emerged not when, at long last, the human race produced somebody clever enough to perceive that artificial conditions would assist in the exploration of nature, but when a rich variety of conditions were fulfilled—including the emergence of questions to which such a procedure promised to provide answers.[10]

To complete our analysis of Aristotle's theory of change, we must briefly consider the celebrated four Aristotelian causes. To understand a change or the production of an artifact is to know its causes (perhaps best translated "explanatory conditions and factors"). There are four of these: the form of a thing; the matter underlying that form, which persists through the change; the agency that brings about the change; and the purpose served by the change. These are called, respectively, formal cause, material cause, efficient cause, and final cause. To take an extremely simple example—the production of a statue—the formal cause is the shape given the marble, the material cause is the marble that receives this shape, the efficient cause is the sculptor, and the final cause is the purpose for which the statue is produced (perhaps the beautification of Athens or the celebration of one of its heroes). There are cases in which identifying one or another of the causes is difficult, or in which one or more causes merge, but Aristotle was convinced that his four causes provided an analytical scheme of general applicability.

We have said enough about the form-matter distinction to make clear what was meant by "formal" and "material" causes, and "efficient" cause is close enough to modern notions of causation to require no further comment; but "final" cause requires explanation. In the first place, the expression "final cause" is an English cognate derived from the Latin word *finis*, meaning "goal," "purpose," or "end," and it has nothing to do with the fact that it often appears last in the list of Aristotelian causes. Aristotle argued, quite rightly, that many things cannot be understood without knowledge of purpose or function. To explain the arrangement of teeth in the mouth, for example, we must understand their functions (sharp teeth in front for tearing, molars in back for grinding). Or to take an example from the inorganic realm, it is not possible to grasp why a saw is made as it is without knowing the function the saw is meant to serve. Aristotle went so far as to give final cause priority over material cause, noting that the purpose of the saw determines the material (iron) of which it must be made, whereas the fact that we possess a piece of iron does nothing to determine that we will make it into a saw.[11]

Perhaps the most important point to be made about final cause is its clear illustration of the role of purpose (the more technical term is "teleology") in Aristotle's universe. The world of Aristotle is not the inert, mechanistic world of the atomists, in which the individual atom pursues its own course mindless of all others. Aristotle's world is not a world of chance and coincidence, but an orderly, organized world, a world of purpose, in which things develop toward ends determined by their natures. It would be unfair and pointless to judge Aristotle's success by the degree to which he anticipated modern science (as though his goal was to answer our questions, rather than his own); it is nonetheless worth noting that the emphasis on functional explanation to which Aristotle's teleology leads would prove to be of profound significance for all of the sciences and remains to this day a dominant mode of explanation within the biological sciences.

COSMOLOGY

Aristotle not only devised methods and principles by which to investigate and understand the world: form and matter, nature, potentiality and actuality, and the four causes. In the process, he also developed detailed and influential theories regarding an enormous range of natural phenomena, from the heavens above to the earth and its inhabitants below.[12]

Let us start with the question of origins. Aristotle adamantly denied the possibility of a beginning, insisting that the universe must be eternal. The alternative—that the universe came into being at some point in time—he regarded as unthinkable, violating (among other things) Parmenidean strictures about something coming from nothing. Aristotle's position on this question would prove troublesome for medieval Christian Aristotelians.

Aristotle considered this eternal universe to be a great sphere, divided into an upper and a lower region by the spherical shell in which the moon is situated. Above the moon is the celestial region; below is the terrestrial region; the moon, spatially intermediate, is also of intermediate nature. The terrestrial or sublunar region is characterized by birth, death, and transient change of all kinds; the celestial or supralunar region, by contrast, is a region of eternally unchanging cycles. That this scheme had its origin in observation would seem clear enough; in his *On the Heavens*, Aristotle noted that "in the whole range of time past, so far as our inherited records reach, no change appears to have taken place either in the whole scheme of the outermost heaven or in any of its proper parts."[13] If in the heavens we observe eternally unvarying circular motion, he continued, we can infer that the heavens are not made of the terrestrial elements, the nature of which (observation reveals) is to rise or fall in transient rectilinear motions. The heavens must consist of an incorruptible fifth element (there are four terrestrial elements): the quintessence (literally, the fifth essence) or aether. The celestial region is completely filled with this quintessence (no void space) and divided, as we shall see, into concentric spherical shells bearing the planets. It had, for Aristotle, a superior, quasi-divine status.[14]

The sublunar region is the scene of generation, corruption, and impermanence. Aristotle, like his predecessors, inquired into the basic element or elements to which the multitude of substances found in the terrestrial region can be reduced. He accepted the four elements originally proposed by Empedocles and subsequently adopted by Plato—earth, water, air, and fire. He agreed with Plato that these elements are in fact reducible to something even more fundamental; but he did not share Plato's mathematical inclination and therefore refused to accept Plato's regular solids and their constituent triangles. Instead, he expressed his own commitment to the reality of the world of sense experience by choosing sensible qualities as the ultimate building blocks. Two pairs of qualities are crucial: hot-cold and wet-dry. These combine in four pairs, each of which yields one of the elements (see fig. 3.2). Notice the use made once again of contraries. There is nothing to forbid any of the four

cold and dry = earth
cold and wet = water
hot and wet = air
hot and dry = fire

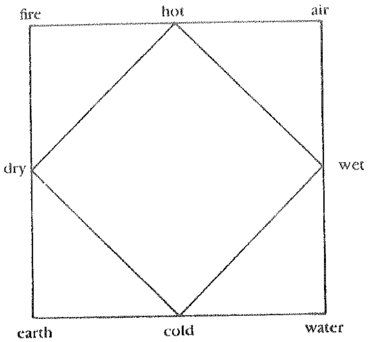


Fig. 3.2. Square of opposition of the Aristotelian elements and qualities. For a medieval (9th c.) version of this diagram, see John E. Murdoch, *Album of Science: Antiquity and the Middle Ages*, p. 352.

qualities being replaced by its contrary, as the result of outside influence. If water is heated, so that the cold of water yields to hot, the water is transformed into air. Such a process easily explains changes of state (from solid to liquid to vapor, and conversely), but also more general transmutation of one substance into another. On such a theory as this, alchemists could easily build.[15]

The various substances that make up the cosmos totally fill it, leaving no empty space. To appreciate Aristotle's view, we must lay aside our almost automatic inclination to think atomistically; we must conceive material things not as aggregates of tiny particles but as continuous wholes. If it is obvious that, say, a loaf of bread is composed of crumbs separated by small spaces, there is no reason not to suppose that those spaces are filled by some finer substance, such as air or water. And there is certainly no simple way of demonstrating, nor indeed any obvious reason for believing, that water and air are anything but continuous. Similar reasoning, applied to the whole of the universe, led Aristotle to the conclusion that the universe is full, a *plenum*, containing no void space. This claim would be attacked by medieval scholars.

Aristotle defended this conclusion with a variety of arguments, such as the following. The speed of a falling body is dependent on the density of the medium through which it falls—the less the density, the swifter the motion of the falling body. It follows that in a void space (density zero), there is nothing to slow the descent of the body, from which we would be forced to conclude that the body would fall with infinite speed—a nonsensical notion, since it implies that the body could be at two places at the same time. Critics have frequently noted that this argument can just as well be taken to prove that the

absence of resistance does not entail infinite speed as to prove that void does not exist. The point is, of course, well taken. However, we need to understand that Aristotle's denial of the void did not rest on this single piece of reasoning. In fact, this was but one small part of a lengthy campaign against the atomists, in which Aristotle battled the notion of void space (or void place) with a variety of arguments, some more and some less persuasive.[16]

In addition to being hot or cold and wet or dry, each of the elements is also heavy or light. Earth and water are heavy, but earth is the heavier of the two. Air and fire are light, fire being the lighter of the two. In assigning levity to two of the elements, Aristotle did not mean (as we might, if we were making the claim) simply that they are less heavy, but that they are light in an absolute sense; levity is not a weaker version of gravity, but its contrary. Because earth and water are heavy, it is their nature to descend toward the center of the universe; because air and fire are light, it is their nature to ascend toward the periphery (that is, the periphery of the terrestrial region, the spherical shell that contains the moon). If there were no hindrances, therefore, earth and water would collect at the center; because of its greater heaviness, earth would achieve a lower position, forming a sphere at the very center of the universe; water would collect in a concentric spherical shell just outside it. Air and fire naturally ascend, but fire, owing to its greater levity, occupies the outermost region, with air as a concentric sphere just inside it. In the ideal case (in which there are no mixed bodies and nothing prevents the natures of the four elements from fulfilling themselves), the elements would thus form a set of concentric spheres: fire on the outside, followed by air and water, and finally earth at the center (see fig. 3.3). But in reality, the world is composed largely of mixed bodies, one always interfering with another, and the ideal is never attained. Nonetheless, the ideal arrangement defines the natural place of each of the elements; the natural place of earth is at the center of the universe, of fire just inside the sphere of the moon, and so forth.[17]

It must be emphasized that the arrangement of the elements is spherical. Earth collects at the center to form *the earth*, and it too is spherical. Aristotle defended this belief with a variety of arguments. Arguing from his natural philosophy, he pointed out that since the natural tendency of earth is to move toward the center of the universe, it must arrange itself symmetrically about that point. But he also called attention to observational evidence, including the circular shadow cast by the earth during a lunar eclipse and the fact that north-south motion by an observer on the surface of the earth alters the apparent position of the stars. Aristotle even reported an estimate by mathematicians of the earth's circumference (400,000 stades = about 45,000 miles, roughly

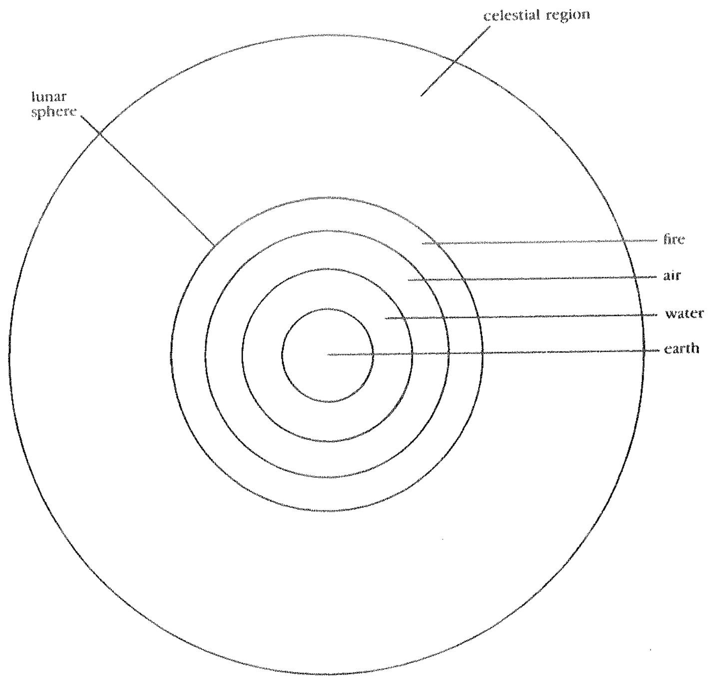


Fig. 3.3. The Aristotelian cosmos.

1.8 times the modern value). The sphericity of the earth, thus defended by Aristotle, would never be forgotten or seriously questioned. The widespread myth that medieval people believed in a flat earth is of modern origin.[18]

Finally, we must note one of the implications of this cosmology, namely that space, instead of being a neutral, homogeneous backdrop (analogous to our modern notion of geometrical space) against which events occur, has properties. Or to express the point more precisely, ours is a world of space, whereas Aristotle's was a world of place. Heavy bodies move toward their place at the center of the universe not because of a tendency to unite with other heavy bodies located there, but simply because it is their nature to seek that central place; if by some miracle the center happened to be vacant (a physical impossibility in an Aristotelian universe, but an interesting imaginary state of affairs), it would remain the destination of every heavy body.[19]

MOTION, TERRESTRIAL AND CELESTIAL

We can best understand Aristotle's theory of motion by grasping its two most fundamental claims. The first is that motion is never spontaneous; there is

no motion without a mover. The second is the distinction between two types of motion: motion toward the natural place of the moving body is "natural" motion; motion in any other direction occurs only under coercion from an outside force and is therefore a "forced" or "violent" motion.

The mover in the case of natural motion is the nature of the body, which is responsible for its tendency to move toward its natural place as defined by the ideal spherical arrangement of the elements. Mixed bodies have a directional tendency that depends on the proportion of the various elements in their composition. When a body undergoing natural motion reaches its natural place, its motion ceases. The mover in the case of forced motion is an external force, which compels the body to violate its natural tendency and move in a direction or manner other than straight-line motion toward its natural place. Such motion ceases when the external force is withdrawn.[20]

So far, this seems sensible. One obvious difficulty, however, is to explain why a projectile hurled horizontally, and therefore undergoing forced motion, does not come to an immediate halt when it loses contact with whatever propelled it. Aristotle's answer was that the medium takes over as mover. When we project an object, we also act on the surrounding medium (air, for instance), imparting to it the power to move objects; this power is communicated from part to part, in such a way that the projectile is always in contact with a portion of the medium capable of keeping it in motion. If this seems implausible, consider the greater implausibility (from Aristotle's standpoint) of the alternative—that a projectile, which is inclined by nature to move toward the center of the universe, moves horizontally or upward despite the fact that there is no longer anything causing it to do so.

Force is not the only determinant of motion. In all real cases of motion in the terrestrial realm, there will also be a resistance or opposing force. And it seemed clear to Aristotle that the quickness of motion must depend on these two determining factors—the motive force and the resistance. The question arose: what is the relationship between force, resistance, and speed? Although it probably did not occur to Aristotle that there might be a quantitative law of universal applicability, he was not without interest in the question and did make several forays into quantitative territory. In reference to natural motion in his *On the Heavens* and again in his *Physics*, Aristotle claimed that when two bodies of differing weight descend, the times required to cover a given distance will be inversely proportional to the weights. (A body twice as heavy will require half the time). In the same chapter of the *Physics*, Aristotle introduced resistance into the analysis of natural motion, arguing that if bodies of equal weight move through media of different densities, the times required to traverse a given distance are proportional to the densities of the respective media; that is, the greater the resistance the slower the body moves. Finally, Aristotle also dealt with forced motion in his *Physics*, claiming that if a given force moves a given weight (against its nature) for a given distance in a given time, the same force will move half that weight twice the distance in that same time (or the same distance in half that time); alternatively, half the force will move half the weight the same distance in the same time.[21]

From such statements, some of Aristotle's successors have made a determined effort to extract a general law. This law is customarily stated as:

$$v \propto F/R.$$

That is, velocity (v) is proportional to the motive force (F) and inversely proportional to the resistance (R). For the special case of the natural descent of a heavy body, the motive force is the weight (W) of the body, and the relationship then becomes:

$$v \propto W/R.$$

Such relationships probably do no great violence to Aristotle's intent for most cases of motion; however, giving them mathematical form, as we have done, suggests that they hold for all values of v, F (or W), and R—a claim that Aristotle would certainly have denied. He stated explicitly, for example, that a resistance equal to the motive force will prevent motion altogether, whereas the formula above offers no such result. Moreover, the appearance of velocity in these relationships seriously misrepresents Aristotle's conceptual framework, which contained no concept of velocity as a quantifiable measure of motion, but described motion only in terms of distances and times. Velocity as a technical scientific term to which numerical values might be assigned was a contribution of the Middle Ages (see below, chap. 12).

Aristotle has been severely criticized for this theory of motion, on the assumption that any sensible person should have recognized its fatal flaws. Is such criticism justified? In the first place, our goal is to understand the behavior, beliefs, and achievements of historical actors against the background of the culture in which they lived, rather than to assess credit or blame according to the degree to which those historical actors resemble us. In short, historians must always contextualize their subjects. Second, some of the criticisms of Aristotle's theories of motion apply only to theories foisted onto Aristotle by followers and critics, rather than to his own. Third, the theory in its genuinely Aristotelian (and properly contextualized) version makes quite good sense today and would surely have made good sense in the fourth century B.C. For example, various surveys have shown that the majority of modern, university-educated people are prepared to assent to many of the basics of Aristotle's theory of motion. Fourth, the relatively modest level of quantitative content in Aristotle's theory is easily explained as the outcome of his larger philosophy of nature. His primary goal was to understand essential natures, not to explore quantitative relationships between such incidental factors as the space-time (or place-time) coordinates applicable to a moving body; even an exhaustive investigation of the latter gives us no useful information about the former. You may criticize Aristotle, if you like, for not being interested in whatever interests modern scientists, but we do not thereby learn anything significant about Aristotle.

Motion in the celestial sphere is an altogether different sort of phenomenon. The heavens, composed of the incorruptible quintessence, possess no contraries and are therefore incapable of qualitative change. It might seem fitting for such a region to be absolutely motionless, but this hypothesis is defeated by the most casual observation of the heavens. Aristotle therefore assigned to the heavens the most perfect of motions—continuous uniform circular motion. Besides being the most perfect of motions, uniform circular motion appears to have the capability of explaining the observed celestial cycles.

By Aristotle's day, these cycles had been an object of study for centuries in the Greek world and for millennia in its predecessor civilizations. It was understood that the "fixed" stars move with perfect uniformity, as though fixed to a uniformly rotating sphere, with a period of rotation of approximately one day. But there were seven stars, the wandering stars or planets, that displayed a more intricate motion, apparently crawling around on the stellar sphere as it went through its daily rotation. These seven were the Sun, Moon, Mercury, Venus, Mars, Jupiter, and Saturn. The sun crawls slowly (about 1°/day), west to east with small variations in speed, through the sphere of fixed stars along a path called the ecliptic, which passes through the center of the zodiac (see fig. 2.6). The moon follows approximately the same course, but at the more rapid rate of about 12°/day. The remaining planets also move along the ecliptic (or in its vicinity) with variable speed and with an occasional reversal of direction.

Are such complex motions compatible with the requirement of uniform circular motion in the heavens? Eudoxus, a generation before Aristotle, had already shown that they are. I will return to this subject in chap. 5; for the moment, it will be sufficient to point out that Eudoxus treated each complex planetary motion as a composite of a series of simple uniform circular movements.

He did this by assigning to each planet a set of concentric spheres, and to each sphere one component of the complex planetary motion. Aristotle took over this scheme, with various modifications. When he was finished, he had produced an intricate piece of celestial machinery, consisting of fifty-five planetary spheres plus the sphere of the fixed stars.

What is the cause of movement in the heavens? Aristotle's natural philosophy would not allow such a question to go unasked. The celestial spheres are composed, of course, of the quintessence; their motion, being eternal, must be natural rather than forced. The cause of this eternal motion must itself be unmoved, for if we do not postulate an unmoved mover, we quickly find ourselves trapped in an infinite regress: a moving mover must have acquired its motion from yet another moving mover, and so on. Aristotle identified the unmoved mover for the planetary spheres as the "Prime Mover," a living deity representing the highest good, wholly actualized, totally absorbed in self-contemplation, nonspatial, separated from the spheres it (or he or she) moves, and not at all like the traditional anthropomorphic Greek gods. How, then, does the Prime Mover or Unmoved Mover cause motion in the heavens? Not as efficient cause, for that would require contact between the mover and the moved, but as final cause. That is, the Prime Mover is the object of desire for the celestial spheres, which endeavor to imitate its changeless perfection by assuming eternal, uniform circular motions. Any reader who has followed this much of Aristotle's discussion would be justified in assuming that there is a single Unmoved Mover for the entire cosmos; it comes as something of a surprise, therefore, when Aristotle announces that, in fact, each of the celestial spheres has its own Unmoved Mover, the object of its affection and the final cause of its motion.[22]

ARISTOTLE AS A BIOLOGIST

There is no way of determining when or how Aristotle became interested in the biological sciences. That his father was a physician is a factor that we must surely take into account. Aristotle's biological studies no doubt occurred over an extended period, but several years on the island of Lesbos (off the coast of Asia Minor) offered him an exceptional opportunity for the observation of marine life. He was probably assisted in the gathering of biological data by his students, and he certainly relied on the reports of other observers, including physicians, fishermen, and farmers. The product of this research effort was a series of large zoological treatises and short works on human physiology and psychology that occupy well over four hundred pages in a modern translation;

these works laid the foundations of systematic zoology and profoundly shaped thought on human biology for some two thousand years.[23]

In Aristotle's day human anatomy and physiology had long attracted attention for their medical import and presumably required no further justification, but Aristotle felt obliged to defend zoological research. In *On the Parts of Animals* he admitted that animals are ignoble by comparison with the heavens and acknowledged that zoological studies are distasteful to many people. However, he considered this distaste to be childish, and he argued that in zoological studies the quantity and richness of the available data compensate for the absence of nobility in the object of study. He argued, moreover, that zoological studies contribute to knowledge of the human frame owing to the close resemblance between animal and human nature; he noted the pleasure of discovering causes in the zoological realm; and he pointed out that order and purpose are displayed with particular clarity in the animal kingdom, providing us with a golden opportunity to refute the atomists' notion that the "works of nature" are products of chance alone.[24]

Aristotle saw that biology has both a descriptive and an explanatory side. He considered the explanation of biological phenomena the ultimate goal, but acknowledged the gathering of biological data as the first order of business. His *History of Animals*, which was intended to meet this first need, is a vast storehouse of biological information. Aristotle began with the human body, as a standard to which other animals could be compared. He subdivided the human body into head, neck, thorax, arms, and legs; and he proceeded to discuss both internal and external features, including brain, digestive system, sexual organs, lungs, heart, and blood vessels.

However, Aristotle made his greatest contribution not in the area of human anatomy but in descriptive zoology. More than five hundred species of animals are mentioned in his *History of Animals*; the structure and behavior of many are described in considerable detail, often on the basis of skillful dissection. Although he devoted considerable attention to the theoretical problems of classification, in practice Aristotle adopted "natural" or popular groupings based on multiple attributes. He divided animals into two major categories—"blooded" (that is, red-blooded) and "bloodless." The former category he subdivided into viviparous quadrupeds (four-footed mammals that bring forth living young), oviparous (or egg-laying) quadrupeds, marine mammals, birds, and fish; the latter into mollusks (such as the octopus and cuttlefish), crustacea (including crabs and crayfish), testacea (including the snail and oyster), and insects. These major categories Aristotle arranged hierarchically in a scale of being according to what he judged to be their degree of vital heat.[25]

Although he ranged over the whole of the animal kingdom, Aristotle was no doubt most at home when it came to marine life, of which he exhibited intimate firsthand knowledge. It has often been noted, for example, that he described the placenta of the dogfish (*Mustelus laevis*) in terms that were not confirmed until the nineteenth century. But Aristotle displayed impressive skill in other parts of the animal kingdom as well. His description of the incubation of birds' eggs is an excellent example of meticulous observation:

> Generation from the egg proceeds in an identical manner with all birds, but the full periods from conception to birth differ. . . . With the common hen after three days and three nights there is the first indication of the embryo. . . . Meanwhile the yolk comes into being, rising towards the sharp end, where the primal element of the egg is situated, and where the egg gets hatched; and the heart appears, like a speck of blood, in the white of the egg. This point beats and moves as though endowed with life, and from it . . . two vein ducts with blood in them trend in a convoluted course . . . , and a membrane carrying bloody fibres now envelops the white, leading off from the vein-ducts. A little afterwards the body is differentiated, at first very small and white. The head is clearly distinguished, and in it the eyes, swollen out to a great extent. . . .[26]

Natural history, which enumerates and describes the population of the universe, is no doubt an appealing occupation and may be regarded by some as an end in itself. But for Aristotle it was a means to a higher end—the source of factual data that would lead to physiological understanding and causal explanations. And for him, true knowledge was always causal knowledge.

Aristotle's understanding of physiology was based on the same principles that functioned in other realms of his natural philosophy. (Whether they were first developed in the biological realm and then applied to metaphysics, physics, and cosmology, or vice versa, is a matter of dispute among scholars.)[27] Thus form and matter, actuality and potentiality, the four causes, and especially the element of purpose or function associated with final cause are central to his biology. Aristotle summarized the ingredients of a proper biological explanation in his *On the Generation of Animals*: "Everything that comes into being or is made must (1) be made out of something, (2) be made by the agency of something, and (3) must become something."[28] That out of which an organism is made is, of course, its material cause; the agency by which it is made is its formal or efficient cause (two causes that are often merged in Aristotle's

biology); and that which it becomes, the goal of its full development, is its final cause.

Each living organism, then, is constituted of matter and form: the matter consists of the various organs that make up the body; the form is the organizing principle that molds these organs into a unified organic whole. Aristotle identified form with organisms' soul and assigned it responsibility for the vital characteristics of the organism—nutrition, reproduction, growth, sensation, movement, and so forth. Indeed, Aristotle arranged living things in a hierarchy on the basis of their participation in several kinds of form or soul, each of which performs certain functions. Plants possess a nutritive soul, which enables them to obtain nourishment, grow, and reproduce. Animals possess, in addition, a sensitive soul, which accounts for sensation and (indirectly) for movement. Finally, humans add to these two lower kinds of soul a rational soul, which supplies the higher capacities of reason. If, as Aristotle maintained, soul is but the form of the organism, then it is clear that soul (including the human soul) is not immortal; at death the organism disintegrates, and its form evaporates into nonbeing. This doctrine would become a bone of contention when Aristotle's works entered the Christian culture of the Middle Ages.[29]

How do Aristotle's metaphysics of form and matter and the four causes explain biological reproduction—one of the central questions of Aristotle's biology? First, Aristotle argued that the existence of two genders—male and female—reflects the distinction between (1) formal or efficient cause (here taken to be the same thing) and (2) the matter on which this cause works. In humans and higher animals the female supplies the matter—namely, menstrual blood. Male semen bears the form and impresses this on the menstrual blood to produce a new organism. The young in higher animals, which have a large measure of vital heat, are brought forth live, as fully developed members of the species; in animals somewhat deficient in vital heat, the offspring are eggs hatched internally; as we descend the scale of perfection, we come to animals that produce eggs hatched externally, the eggs being more or less perfect depending on the exact degree of heat; at the bottom of the scale, bloodless animals produce a grub or maggot:

> We must observe how rightly Nature orders generation in regular gradation. The more perfect and hotter animals produce their young perfect in respect of quality . . . , and these generate living animals within themselves from the first. The second class do not generate perfect animals within themselves from the first (for they are only viviparous after first

laying eggs). . . . The third class do not produce a perfect animal, but an egg, and this egg is perfect. Those whose nature is still colder than these produce an egg, but an imperfect one, which is perfected outside the body. . . . The fifth and coldest class does not even lay an egg from itself; but so far as the young ever attain to this condition at all, it is outside the body of the parent. . . . For insects produce a grub first; the grub after developing becomes egg-like.[30]

The idea of perfection, so prominent in Aristotle's theory of generation, brings us to the third and last element of biological explanation—final cause or that which a biological organism is in the process of becoming. The biologist, in Aristotle's view, always needs to know the complete, mature form or nature of an organism. Only such knowledge will enable him to understand the structure of the organism and the existence and interrelations of its parts. For example, Aristotle explained the presence of lungs in land animals by reference to the needs of the organism as a whole. Blooded animals, he argued, require an external cooling agent because of their warmth. In fish, this agent is water, and consequently fish have gills instead of lungs. Animals that breathe, however, are cooled by air and consequently come equipped with lungs.[31] Knowledge of the mature form is also part of the explanation of the organism's development, for there is an upward movement in the organic realm, as organisms strive to actualize the potentialities that exist within them. We cannot understand the changes that occur within an acorn, for example, if we do not understand the oak tree that is its final destination. Finally, purpose and function enter Aristotle's biology not merely as an explanation of the form or development of the individual or species, but on a universal or cosmic level, to explain the interdependence and interrelationships of species in the order of nature.

There is, of course, much more to Aristotle's biological system. He explained nutrition, growth, locomotion, and sensation. He considered the functions of the principal organs, including brain, heart, lungs, liver, and reproductive organs. It is important to note that he made the heart the central organ of the body, the seat of emotions and sensation as well as of vital heat. He developed the notion of hierarchy in the biological realm: form, he believed, is superior to matter, living to nonliving, male to female, blooded to bloodless, mature to immature. Indeed, he arranged living things in a single, hierarchical scale of being, beginning with the Prime Mover at the top and descending through the human race to viviparous, oviparous, and vermiparous animals, and finally to plants.

Let us conclude this discussion with a brief analysis of method in Aristotle's biological works. If there is any branch of the scientific enterprise that demands observation, surely it is biology (and especially natural history). It is inconceivable that Aristotle would have attempted to describe the structure and habits of animals on any other basis. The observation in question was frequently his own, and we find in his works plentiful evidence of empirical method, including dissection. However, no naturalist working alone could amass the quantity of data contained in Aristotle's biological works, and it is apparent that he relied on the reports of travelers, farmers, and fishermen, the help of assistants, and the writings of his predecessors. Aristotle was generally critical of his sources, and displayed a healthy skepticism even about his own observations. However, he was not always skeptical enough, and there are many examples of descriptive error in his biological works. When it came to biological theory, Aristotle (like any theorist) was obliged to make inferences from the observational data; if his inferences were not always the ones we would make, they nonetheless display the insight of one of the most brilliant biologists ever to live. They also, of course, display the powerful influence of Aristotle's larger philosophical system, which continually influenced the questions he asked, the details he noticed, and the theoretical interpretation he placed upon them.[32]

ARISTOTLE'S ACHIEVEMENT

My frequent mini-lectures on proper historical methodology may seem to be the flogging of a dead horse, but conscience requires me to continue until I am certain that this particular horse has succumbed. The proper measure of a philosophical system or a scientific theory is not the degree to which it anticipated modern thought, but its degree of success in treating the philosophical and scientific problems of its own day. If a comparison is to be made, it must be between Aristotle and his predecessors, not Aristotle and the present. Judged by such criteria, Aristotle's philosophy is an astonishing achievement. In natural philosophy, he offered a subtle and sophisticated treatment of the major problems posed by the pre-Socratics and Plato: the nature of the fundamental stuff, the proper means of knowing it, the problems of change and causation, the basic structure of the cosmos, and the nature of deity and its relationship to material things.

But Aristotle also went far beyond any predecessor in the analysis of specific natural phenomena. It is no exaggeration to claim that, almost single-handedly, he created entirely new disciplines. His *Physics* contains a detailed discussion of terrestrial dynamics. He devoted the better part of his *Meteorology* to phenomena of the upper atmosphere, including comets, shooting stars, rain and the rainbow, thunder, and lightning. His *On the Heavens* developed the work of certain predecessors into an influential account of planetary astronomy. He touched upon geological phenomena, including earthquakes and mineralogy. He undertook a thorough analysis of sensation and the sense organs, particularly vision and the eye, developing a theory of light and vision that would remain influential until the seventeenth century. He concerned himself with what we might regard as the basic chemical processes—mixtures and combinations of substances. He wrote a book on the soul and its faculties. And, as we have seen, he contributed monumentally to developments in the biological sciences.

We will consider Aristotle's influence in subsequent chapters. I will conclude here simply by stating that his powerful influence in late antiquity and his dominance from the thirteenth century through the Renaissance resulted not from intellectual subservience on the part of scholars during those periods or from interference on the part of the church, but from the overwhelming explanatory power of Aristotle's philosophical and scientific system. Aristotle prevailed through persuasion, not coercion.

29. In the Babylonian sexagesimal (base 60) system of counting, there are 360 degrees in a circle, 60 minutes in a degree, 60 seconds in a minute, and 60 thirds in a second. According to this tablet, the increase or decrease in speed (measured in degrees) between one month and the next is on the order of a third of a degree.

30. Sigerist, *History of Medicine*, 1:276. On Egyptian medicine, besides Sigerist, see Paul Ghalioungui, *The House of Life, Per Ankh: Magic and Medical Science in Ancient Egypt*; Ghalioungui, *The Physicians of Pharaonic Egypt*; John R. Harris, "Medicine." On surgery, see Guido Majno, *The Healing Hand*, chap. 3.

31. B. Ebbell, *The Papyrus Ebers*.

32. James H. Breasted, *The Edwin Smith Surgical Papyrus*.

33. On Mesopotamian medicine, see Sigerist, *History of Medicine*, 1, pt. 4; Robert Biggs, "Medicine in Ancient Mesopotamia"; Majno, *Healing Hand*, chap. 2.

CHAPTER TWO

1. Homer, *The Odyssey*, trans. Robert Fagles, pp. 77–78.

2. On the authorship, dating, and historicity of the *Odyssey*, see Bernard Knox's introduction to ibid.

3. Hesiod, *Theogony and Works and Days*, trans. M. L. West, pp. 6–7.

4. *The Poems of Hesiod*, trans. R. M. Frazer, p. 32. See also Robert Graves, *The Greek Myths*, vol. 1; Friedrich Solmsen, *Hesiod and Aeschylus*.

5. See the interesting analysis of this problem by Paul Veyne, *Did the Greeks Believe in Their Myths?*

6. On early Greek philosophy, see especially the following books by G. E. R. Lloyd: *Early Greek Science: Thales to Aristotle*, chap. 1; *Magic, Reason, and Experience*; *The Revolutions of Wisdom*; *Methods and Problems in Greek Science*; and (with Nathan Sivin), *The Way and the Word*. See also G. S. Kirk and J. E. Raven, *The Presocratic Philosophers*; Jonathan Barnes, *Early Greek Philosophy*.

7. On the early Greeks, see Thomas Cahill, *Sailing the Wine-Dark Sea: Why the Greeks Matter*, pp. 9–14.

8. *Metaphysics*, I.3, 983a6–20; portions of trans. borrowed from Kirk and Raven, *Presocratic Philosophers*, p. 87; from Aristotle, *Complete Works*, ed. Jonathan Barnes; and from the trans. of Hugh Tredennick in the Loeb Classical Library. On the Milesians, see Lloyd, *Early Greek Science*, chap. 2, and works cited above in n. 6.

9. Kirk and Raven, *Presocratic Philosophers*, pp. 108–9.

10. Simplicius quoting Theophrastus, ibid., p. 144.

11. G. E. R. Lloyd, *Demystifying Mentalities*, esp. chap. 1; Lloyd, *Early Greek Science*, pp. 10–15.

12. Kirk and Raven, *Presocratic Philosophers*, pp. 1–9; Gregory Vlastos, *Plato's Universe*, pp. 5–10.

13. Plato, *Cratylus*, 402a; Kirk and Raven, *Presocratic Philosophers*, p. 97.

14. On the atomists, see David Furley, *The Greek Cosmologists*, chaps. 9–11; Kirk and Raven, *Presocratic Philosophers*, chap. 17; Jonathan Barnes, *The Presocratic Philosophers*, 2:40–75; Cyril Bailey, *The Greek Atomists and Epicurus*.

15. See the papers in Christoph Lüthy, John E. Murdoch, and William Newman, eds., *Late Medieval and Early Modern Corpuscular Matter Theories*, esp. Newman's article, pp. 291–329.

16. For Thales on the gods, see Lloyd and Sivin, *The Way and the Word*, p. 145.

17. Kirk and Raven, *Presocratic Philosophers*, pp. 328–29; Furley, *Greek Cosmologists*, chap. 7.

18. Aristotle, *Metaphysics*, I.5.985b33–986a2, in Aristotle, *Complete Works*, 2:1559. On the Pythagoreans, see also Kirk and Raven, *Presocratic Philosophers*, chap. 9; Furley, *Greek Cosmologists*, chap. 5; Barnes, *Presocratic Philosophers*, 2:76–94; Lloyd, *Early Greek Science*, chap. 3.

19. Kirk and Raven, *Presocratic Philosophers*, chap. 6; Vlastos, *Plato's Universe*, pp. 6–10.

20. On Parmenides, see Kirk and Raven, *Presocratic Philosophers*, chap. 10; Furley, *Greek Cosmologists*, pp. 36–42; Lloyd, *Early Greek Science*, pp. 37–39; Barnes, *Presocratic Philosophers*, 1: chaps. 10–11.

21. Kirk and Raven, *Presocratic Philosophers*, chap. 11; Barnes, *Presocratic Philosophers*, 1: chaps. 12–13. Aristotle's comment is found in his *Physics*, VI.2.233a22–23. In a second paradox, Zeno describes a race between Achilles (noted for his swiftness) and a tortoise (noted for its slowness): if the tortoise is given a head start, however small, Achilles will never be able to catch it, since by the time Achilles reaches the tortoise's starting point, the tortoise will have moved beyond it to a new position; by the time Achilles reaches this new position, the tortoise will have moved beyond that; and so on, ad infinitum.

22. Lloyd, *Early Greek Science*, chap. 4; Kirk and Raven, *Presocratic Philosophers*, chaps. 14, 17.

23. Kirk and Raven, *Presocratic Philosophers*, p. 422. See also Lloyd, *Early Greek Science*, chap. 4.

24. Kirk and Raven, *Presocratic Philosophers*, pp. 325, 394.

25. The scholarship on Plato is enormous. I have been heavily influenced by Vlastos, *Plato's Universe*, and the translation-commentaries of the various Platonic dialogues by Francis M. Cornford. For brief, recent introductions, see R. M. Hare, *Plato*; David J. Melling, *Understanding Plato*.

26. Plato, *Republic*, bk. VII, 514a–521b.

27. Lloyd, *Early Greek Science*, pp. 68–72; Plato, *Phaedo*, 65b; Plato, *Republic*, bk. VII, 532, trans. Francis M. Cornford, p. 252.

28. Vlastos, *Plato's Universe*, chap. 2. On Plato's cosmology, see also *Plato's Cosmology: The "Timaeus" of Plato*, trans. and commentary by Francis M. Cornford; Richard D. Mohr, *The Platonic Cosmology*.

29. Vlastos, *Plato's Universe*, chap. 3.

30. Ibid., chap. 2

31. The quoted passages are from *Plato's Cosmology*, 30d, p. 40, and 34b, p. 58.

32. Vlastos, *Plato's Universe*, pp. 61–65; Friedrich Solmsen, *Plato's Theology*.

CHAPTER THREE

1. For more on the Lyceum, see below, chap. 4. On Aristotle's relationship to Alexander, see Peter Green, *Alexander of Macedon*, pp. 53–62.

2. There is a great deal of excellent introductory literature on Aristotle; see especially G. E. R. Lloyd, *Aristotle: The Growth and Structure of His Thought*; Jonathan Barnes, *Aristotle*; Abraham Edel, *Aristotle and His Philosophy*.

3. Barnes, *Aristotle*, pp. 32–51; Edel, *Aristotle*, chaps. 3–4; Lloyd, *Aristotle*, chap. 3.

4. The technical name for this Aristotelian doctrine is "hylomorphism"—from *hyle* and *morphe*, the Greek terms for matter and form.

5. Aristotle's epistemology is dealt with in Edel, *Aristotle*, chaps. 12–15; Lloyd, *Aristotle*, chap. 6; Jonathan Lear, *Aristotle: The Desire to Understand*, chap. 4; Marjorie Grene, *A Portrait of Aristotle*, chap. 3.

6. On this subject, see Jonathan Barnes, "Aristotle's Theory of Demonstration"; G. E. R. Lloyd, *Magic, Reason, and Experience*, pp. 200–220.

7. On change, see Edel, *Aristotle*, pp. 54–60; Sarah Waterlow, *Nature, Change, and Agency in Aristotle's "Physics,"* chaps. 1, 3.

8. For Aristotle's conception of "nature," see Sarah Waterlow, *Nature, Change, and Agency*, chaps. 1–2; Edel, *Aristotle*, chap. 5 (p. 71 for the quoted phrase); James A. Weisheipl, "The Concept of Nature."

9. Aristotle was explicit about this in his *Politics*, instructing that "we must look for the intentions of nature in things which retain their nature, and not in things which are corrupted." *Politics*, I.4, 1254a35–37, trans. B. Jowett, in Aristotle, *Complete Works*, 2:1990.

10. See especially Peter Harrison's forthcoming *Adam's Encyclopaedia: The Fall of Man and the Foundations of Science, 1500–1700*; also Waterlow, *Nature, Change, and Agency*, pp. 33–34; Ernan McMullin, "Medieval and Modern Science: Continuity or Discontinuity?" pp. 103–29, esp. 118–19.

11. Edel, *Aristotle*, chap. 5.

12. See especially Friedrich Solmsen, *Aristotle's System of the Physical World*; Lloyd, *Aristotle*, chaps. 7–8.

13. *On the Heavens*, I.4.270b13–16, quoted from Aristotle, *Complete Works*, ed. Barnes, 1:451.

14. Lloyd, *Aristotle*, chap. 7.

15. Ibid., chap. 8. On alchemy, see below, chap. 12.

16. For Aristotle on the void, see Solmsen, *Aristotle's System of the Physical World*, pp. 135–43; David Furley, *Cosmic Problems*, pp. 77–90.

17. Furley, *Cosmic Problems*, chaps. 12–13.

18. Aristotle dealt with the shape of the earth in *On the Heavens*, II.13. See also D. R. Dicks, *Early Greek Astronomy to Aristotle*, pp. 196–98. The myth that ancient and medieval people believed in a flat earth is discussed below in chap. 7.

19. Waterlow, *Nature, Change, and Agency*, pp. 103–4.

20. For a careful analysis of the fine points, see James A. Weisheipl, "The Principle *Omne quod movetur ab alio movetur* in Medieval Physics."

21. On natural motion, see Aristotle's *On the Heavens*, 1.6, and *Physics*, IV.8. On forced motion, see *Physics*, VIII.5. For discussion, see Marshall Clagett, *The Science of Mechanics in the Middle Ages*, pp. 421–33; Clagett, *Greek Science in Antiquity*, pp. 64–68.

22. Lloyd, *Aristotle*, pp. 139–58.

23. There has been a recent burst of interest in Aristotle's biology. See especially three books by G. E. R. Lloyd: *Aristotelian Explorations*; *Aristotle*, chap. 4; and *Early Greek Science*, pp. 115–24. See also Anthony Preus, *Science and Philosophy in Aristotle's Biological Works*; Martha Craven Nussbaum, *Aristotle's "De motu animalium"*; Pierre Pellegrin, *Aristotle's Classification of Animals*; Allan Gotthelf and James G. Lennox, eds., *Philosophical Issues in Aristotle's Biology*.

24. Aristotle, *On the Parts of Animals*, 1.5. See also Lloyd, *Aristotle*, pp. 69–73.

25. Lloyd, *Aristotle*, pp. 76–81, 86–90; Lloyd, *Early Greek Science*, pp. 116–18; Pellegrin, *Aristotle's Classification of Animals*.

26. *History of Animals*, VI.3.561a3–19, in *Complete Works*, 1:883.

27. Lloyd, *Aristotle*, pp. 90–93; D. M. Balme, "The Place of Biology in Aristotle's Philosophy."

28. Aristotle, *De generatione animalium*, II.1.733b25–27, in *Complete Works*, 1:1138.

29. On Aristotle's doctrine of the soul and its faculties, see Lloyd, *Aristotle*, chap. 9; Ross, *Aristotle*, chap. 5; J. L. Ackrill, *Aristotle the Philosopher*, pp. 68–78. On medieval reactions, see chap. 10, below.

30. Aristotle, *De generatione animalium*, II.1.733a34–733b14, in *Complete Works*, ed. Barnes, 1:1138. On biological reproduction, see also Ross, *Aristotle*, pp. 117–22; Preus, *Science and Philosophy in Aristotle's Biological Works*, pp. 48–107.

31. Aristotle, *On the Parts of Animals*, III.6.668b33–669a7. On teleology in Aristotle's biology, see also Ross, *Aristotle*, pp. 122–27; Nussbaum, *Aristotle's "De motu animalium,"* pp. 59–106.

32. On method in Aristotle's biology, see Lloyd, *Aristotle*, pp. 76–81; Lloyd, *Magic, Reason, and Experience*, pp. 211–20; Nussbaum, *Aristotle's "De motu animalium,"* pp. 107–42.

CHAPTER FOUR

1. The classic sources on ancient education, to be used with caution, are H. I. Marrou, *A History of Education in Antiquity*; Werner Jaeger's three-volume *Paideia: The Ideals of Greek Culture*. For more recent scholarship, see John Patrick Lynch, *Aristotle's School*; Robin Barrow, *Greek and Roman Education*.

2. Lynch, *Aristotle's School*, pp. 65–66. On sophistic teaching in general, see pp. 38–54.

3. On Plato's Academy, see Lynch, *Aristotle's School*, pp. 54–63; Harold Cherniss, *The Riddle of the Early Academy*.

4. Cherniss, *Riddle of the Early Academy*, p. 65.

5. On the Lyceum, see Lynch, *Aristotle's School*, chaps. 1, 3; also Felix Grayeff, *Aristotle and His School*.