Part I

Introduction to Part I

1 The Unbroken Thread

The various scientific disciplines as we know them today have distinctive characteristics by which even the uninitiated can recognize them. Physics has intricate equations and imposing particle accelerators, astronomy boasts orbital telescopes and maps of supergalactic clusters, biology has a sweeping evolutionary narrative and describes proteins that fold into exact three- dimensional shapes to catalyze reactions, chemistry proudly displays its periodic table and produces numberless new compounds that find their way into the surgical room and the supermarket. And the disciplines are linked in important ways. Geology intersects with both evolutionary biology and physics. Physicists are as interested in the periodic table as chemists. Biochemistry straddles the disciplinary division between biology and chemistry. Astronomers make use of physics to describe exotic objects like black holes and to understand stellar evolution.

But as we work our way backwards in time, the view becomes less and less familiar. Much of the technology that is the cultural signature of physics and chemistry disappears by the time we cross the 1900 line. When we move back to 1850, biology has lost its grand unifying vision and chemistry has lost its table of the elements. Prior to 1800 chemistry looks even less familiar, with odd substances like phlogiston and caloric populating the textbooks. Biology is largely reduced to anatomy and conjectural taxonomy, and its connections to chemistry and geology are severed.

Even as far back as 1700, at least physics and astronomy look like threadbare versions of their modern selves. But when we retreat backwards across the 1600 line, the fabric of science unravels with shocking abruptness. Physics is shorn of its mathematical tools, including calculus and modern algebra, and the foundations of elementary dynamics are in disarray. Telescopes and microscopes have disappeared. What passes for chemistry is inseparable from alchemy, and astronomers eke out their incomes by casting horoscopes for the nobility. The majority opinion is that the earth does not orbit the sun or rotate on its axis, and fundamental biological facts such as the circulation of the blood are unknown.

We might stop there and declare that, prior to 1600, science simply did not exist. But on a closer look this drastic pronouncement appears too simplistic. Though the technology and even the fundamental principles of all the major sciences are absent, there remain recognizable similarities of aim and purpose. It is not just that we recognize, beneath the strange terminology of alchemy and surrounded by a good deal of nonsense, bits of true empirical lore; the more significant fact is that the alchemists are actively seeking a set of basic principles that govern the transformations of matter. In astronomy, the models of the solar system are complex geometrical nightmares; but the underlying aim of giving a rational account of the motions of the sun, moon, planets, and stars remains. In anatomy the leading thinkers are investigating the structure of the human body with great attention to detail, and in medicine the best minds are hunting for the causes of disease and the mechanisms of contagion. In the aims of these Renaissance disciplines, we can see a thread of continuity stretching from that era to our own.

Moving carefully backwards through the Middle Ages we find that this thread, though perilously thin, is never quite broken. We see it in Paris during the 1300s. It virtually disappears from the west prior to 1100 but remains visible in the work of Arab and Persian and Jewish scholars in Baghdad and Cordoba and Damascus and Fez. In the 500s, it surfaces in Alexandria. Moving back before the fall of Rome we find it in Italy, and other threads appear across the Roman Empire. Before the dawn of the Christian era these threads stretch back into Greece, where for a brief and glorious period they draw together into a vivid conceptual ribbon woven in rich texture with strange but explicit designs. Back through Archimedes and Euclid, Aristotle and Plato, Epicurus and Democritus and Empedocles and Pythagoras and Thales we can trace it, though the ribbon narrows to a mere thread again at the earliest parts of this period.

And there at last, somewhere around 600 BC, the thread disappears altogether.

This is why we must begin our study of the history of science with the Greeks. They were the first thinkers known to us who clearly articulated the idea that the world is a *cosmos*, an ordered whole governed by rationally discoverable principles. The earliest conjectures regarding the nature of those principles look wholly foreign to us, even absurd. Thales guessed that the fundamental stuff out of which all things are made is water, Anaximander suggested that it was something formless and boundless, Anaximenes thought it was air, and Xenophanes took it to be earth. But their varied and incompatible answers are far less interesting than the assumption lying behind the question they all seek to answer: the assumption that there *is* a fundamental kind of stuff and that the bewildering complexity of the visible world is in some way a function of a simpler underlying order.

2 Greek Science and Greek Philosophy

The early history of science is largely a history of philosophical ideas regarding the nature and structure both of the cosmos and of our knowledge of it. Philosophy and science flourished together in the golden age of Greece; indeed, the line between them was not as sharply drawn as it is today, and in many cases it is difficult to say where philosophy ends and science begins. Aristotle's voluminous writings provide a case in point. In founding the discipline of logic, for example, Aristotle does more than to codify some principles of correct reasoning and list some common fallacies; he fashions syllogistic logic with one eye on the metaphysics of essences and the other on the structure of scientific knowledge. Scientific knowledge, according to Aristotle, is *demonstrative*: it is arrived at by rigorous reasoning from premises that are themselves known and not merely conjectured. An infinite regress threatens, each item of knowledge requiring others to be known first. Aristotle sees and resolves this problem by developing a version of foundationalism, the view that all scientific knowledge rests in the end on primary certainties that are known immediately rather than by derivation from anything else.

The analogy here with mathematics is very strong, and this is no accident. Aristotle wrote about one generation before Euclid, and geometry, already a well-developed branch of learning, provided a compelling model of structured and certain knowledge. But in the case of geometry, the foundations are – most of them – intuitively compelling. It is natural to ask whether the analogy can be pressed at this point. Are there also intuitively compelling foundations for biology, astronomy, and the other sciences? If so, what are they? And by what means can we identify them?

Aristotle's answer is suggestive but frustratingly inexplicit: in experience we *recognize*, somehow, the universal implicit in a few particular instances. In one sense this is plausible enough. We see many cats that differ in size and color and shape of head, but they are all similar; later when we see another cat we can recognize that it is the same type of creature. But does this experience give us knowledge of the *essence* of felines – that is, of their true nature? And is that knowledge certain, so that the conclusions we deduce from it will also be certainties? These are high standards. Aristotle is well aware that mere enumeration of instances does not guarantee knowledge of essences; the mental move he calls *epagoge*, in which the mind rises from perception of particulars to knowledge of universals, cannot be flattened out into anything like induction in the modern sense. For the next two millennia, some of the best minds in the world wrestled with the problems posed by Aristotle's account of the structure and foundations of scientific knowledge.

A second strand of Greek thought about scientific knowledge is no less important: science aims to give us not merely *foresight* but *understanding*. Predictive astronomy is older than the attempt to understand *why* things happen in the heavens. Babylonian cuneiform tablets bearing dated records of astronomical events reach as far back as 747 BC, and star catalogues and records of planetary motions go back a millennium before that. From such data it is possible to extrapolate the motions of the sun, moon, and planets against the background of the fixed stars. This is no mean computational feat. Mars, for example, generally progresses through the constellations of the zodiac in a fixed direction; but at intervals it appears to reverse itself, backtracks, then doubles back again and proceeds in its original direction, losing about four months and creating a looped path against the background of stars. Something similar occurs in the motion of all of the planets. Astronomers call this detour "retrograde motion." The Babylonians knew of retrograde motion and could even predict it. But we have no record that they ever speculated as to *why* it occurs.

By contrast, the Greeks were almost obsessed with understanding why things happen. In the *Republic* Plato puts in the mouth of Socrates an allegory in which the cosmos is depicted as a sort of spinning top with eight concentric shells, corresponding to the stars, sun, moon, and the five known planets, rotating independently at different rates of speed. The model is crude, and it makes no provision for retrograde motion, but it is a first step toward trying to make the motions of the heavenly bodies understandable. In the second century AD, Claudius Ptolemy, relying heavily on the work of Hipparchus from three centuries earlier, produced a completely different model in which the planets ride on the circumferences of circles called epicycles, and each epicycle rides on the circumference of a larger circle, with the earth standing motionless near the center of the whole system. The complete construction, which sometimes involves epicycles upon epicycles and epicycles oriented vertically to account for latitudinal motions of the planets, is enormously complex. It yields, however, reasonably accurate predictions for the visible motions of all of the major heavenly bodies.

But was the resulting construct real? Was this the way the heavens were constituted? Once asked, the question could not be retracted. If the goal of science is to give knowledge not just of the fact but of the *reasoned* fact, as Aristotle puts it, then mere guesses at the hidden mechanism of the universe could never suffice. In the long history of commentary both on Aristotle and on Ptolemy there is much more than mere servile endorsement. Aristotle's views were widely contested in both space and time – in Alexandria in the sixth century, in Baghdad and Damascus and Fez in the tenth through the twelfth, in Paris in the thirteenth and fourteenth, in Saragossa in the fifteenth. The criticism was sharper and more widespread in active centers of learning than it was in places where, for whatever reason, intellectual activity had fallen off. But the Victorian notion that Aristotle's teachings went unchallenged during the Middle Ages is simply a myth.

Similarly, one thinker after another struggled to come to terms with Ptolemy's geometrically outlandish system. Is predictive accuracy evidence of truth? If not, how can we ever hope to discover the real causes of phenomena? Should we dismiss epicycles as useful fictions, mere calculating devices not to be taken literally? Where, then, is the reasoned fact? Are we doomed to agnosticism regarding the true explanations of planetary motions? If so, how much more profound must be our ignorance of the more complex phenomena of the natural world around us.

Despite fairly widespread skepticism about its parts, Aristotle's view of nature remained dominant through the end of the sixteenth century. If his views on projectile motion, for example, seemed far-fetched, the problem could be tabled pending further research or patched up by replacing faulty components piecemeal, as happened with the introduction of impetus into the larger Aristotelian framework. A grand synthesis, even one with known flaws, is not easily set aside; it generally requires a rival synthesis to challenge and replace it.

Although telescopes and microscopes come readily to mind when we think of the interplay of science and technology, arguably the single most significant technological contribution to the overthrow of the Aristotelian world picture was the invention of moveable type around 1450. From the early sixteenth century onward, information and arguments were disseminated at a rate unimaginable in medieval times, exponentially increasing the exposure given to new theories and ideas.

3 The Revolution from Copernicus to Newton

Ironically, the first printed book to create a major crack in the Aristotelian edifice was inspired by the desire to be faithful to Aristotle. Nicolas Copernicus, horrified by the liberties Ptolemy had taken with Aristotle's views on motion, inverted the structure of the Ptolemaic cosmos and set the earth in motion while holding the sun still. Such a view accorded better than the Ptolemaic one with Aristotle's prescription of uniform circular motion for heavenly bodies, and it revealed some truly beautiful harmonies among the motions of the earth and the planets. Yet Copernicus's new view faced observational difficulties and caused tensions with Aristotle's physics, tensions that Copernicus himself was unable to resolve. From the publication of Copernicus's work in 1543 it took almost a century and a half and the work of three brilliant and utterly different minds to overcome these obstacles and found a new physics.

The first was Galileo Galilei, the brilliant Italian astronomer, mathematician, and physicist, who used the newly invented telescope to overturn observational objections to the Copernican view and even to turn observations into arguments in its favor. That alone would have guaranteed Galileo immortality in the annals of science; but it was the lesser half of his achievement. Utterly persuaded of the truth of the Copernican view, Galileo set out to overthrow the principles of Aristotelian physics that were at variance with it. The discussion of physics in Galileo's *Dialogue Concerning the Two Chief Systems of the World* provides both a powerful critique of Aristotelian physics and the first recognizably modern, if still not quite correct, account of inertia.

The second was one of Galileo's contemporaries, the intense German mathematician and astronomer Johannes Kepler. Where Galileo's mind cut through the clutter of details to get to the heart of the matter, Kepler's mind reveled in details and found myriad patterns, some of them spurious, hidden in mountains of data. Galileo, moved by the need to present a simple and persuasive account of the Copernican theory, omits mention of Copernicus's numerous epicycles; Kepler sets out to find the true orbit of Mars and ends up dispensing with circular motion altogether in favor of an elliptical orbit. Yet the longing for celestial harmonies binds all three great astronomers together. In Kepler's case it issues in three elegant laws of planetary motion that bear his name.

The third intellectual giant, and the one who actually completed the revolution, was Isaac Newton. With unerring instinct Newton took the best from each of his great predecessors and left the dross. From Galileo he took the idea of terrestrial inertia, but in the corrected form advanced by Descartes. From Kepler he took the three laws of planetary motion, but he left aside Kepler's wilder speculations regarding the Platonic solids and the music of the spheres. Combining these materials with the accurate observations of John Flamsteed, the first Astronomer Royal, Newton created a synthesis of unparalleled scope that accounted, using one unified set of laws, for the fall of an apple, the orbit of the moon, and the ebb and flow of the tides. And Newton had the mathematical power to go beyond plausible speculation. In an intellectual *tour de force* he proved that a centrally directed force would result in Kepler's second law, proved that the mass of a spherical solid would exert a gravitational attraction on other bodies as if all of its mass were concentrated at the central point, and proved that an inverse square law of gravitational attraction would produce an elliptical orbit. It is only a slight overstatement to say that before Newton no one was quite sure whether one set of laws could account for all the phenomena of the heavens and the earth, while after Newton no one doubted it.

4 The Biological Side of the Scientific Revolution

While the revolution in astronomy and dynamics was flowering, a parallel revolution was unfolding in anatomy and biology. In 1543, the same year that Copernicus's *On the Revolutions of the Heavenly Spheres* appeared, the young physician Andreas Vesalius published *On the Fabric of the Human Body* with outstanding woodcuts by the Flemish artist Jan Kalkar. Vesalius challenged a number of assertions of the Greek physician Galen, notably regarding the supposed existence of pores in the septum of the heart. The ink on the pages of Vesalius's book had scarcely dried when the Italian physician Girolamo Fracastoro published *On Contagion* (1546), in which he advanced the thesis that various diseases were each caused by a specific agent that could be spread by either by direct contact with someone already infected or by more indirect means such as contact with cloth or linens that could foster the "essential seeds" of the contagion. The crowning achievement of Renaissance anatomy was the discovery of the circulation of the blood, postulated by Michael Servetus in 1553 and announced, with compelling arguments, by William Harvey in 1616.

All of these advances took place before the development of even crude microscopes. But advances in optics in the seventeenth century opened new vistas for biology as well as for astronomy. Robert Hooke's *Micrographia* (1664), which contained large fold-out pictures of insects such as the flea and the louse as seen through the microscope, was wildly popular and established the reputation of the Royal Society. The Dutch scientist Antony van Leeuwenhoek (1632–1723) discovered an ingenious trick for creating tiny spherical lenses that could magnify up to 300 diameters, and using these lenses he discovered microscopic single-celled organisms.

5 The Rise of Modern Philosophy

As it had in the golden age of Greece, the sudden upsurge in scientific theorizing in the sixteenth and seventeenth centuries dovetailed with fresh work on the foundations of scientific knowledge. We can date the beginnings of self-conscious reflection on the philosophical implications of the new science and the scientific implications of the emerging philosophy from about 1600. In the early years of the seventeenth century, Francis Bacon (1561–1626), Lord Chancellor of England, wrote several works decrying the sterility of scholastic philosophy and outlining a new program for experimental philosophy and the organization of scientific societies. The French philosopher and mathematician René Descartes (1596–1650) strove to provide both better foundations for knowledge and better mechanics than Aristotle. John Locke (1632–1704), fellow of the Royal Society and friend of such luminaries as Robert Hooke (1635–1703) and Isaac Newton (1642–1727), wrote his monumental *Essay Concerning Human Understanding* in an attempt to explain the empiricist epistemological underpinnings of the new science.

The enormous success of Newton's mechanical picture of the universe and the emergence of the new optical technology triggered an avalanche of scientific and philosophical work in the eighteenth century. The mathematical elaboration of calculus, using Leibniz's notation rather than Newton's, enabled astronomers to put the finishing touches on celestial mechanics. But with the new science came new questions. What is light, a rain of particles or a vibration in an intervening medium between the luminous object and the eye? What is the nature of space? Would it still exist if all objects were to disappear? How is learning from experience possible at all? What do we really mean by "cause and effect," and how can we move from bare sensory impressions to justified belief in causal claims? How do we come to know the geometric structure of space?

One critical philosophical development accompanying the scientific revolution was the shift from the Aristotelian conception of science as absolutely certain knowledge derived from first principles to a more modest conception of science as a rational but fallible discipline. It proved extraordinarily difficult to find the right balance between optimism and pessimism. Locke laid out an empiricist approach that would suffice to let us know what we need for practical purposes, but he had doubts about our ability to discover the hidden mechanisms of nature. David Hume (1711–1776) refined Locke's modest empiricism and pushed it into skepticism. Immanuel Kant (1724–1804), provoked by Hume's arguments but dissatisfied with his skepticism, developed an elaborate form of idealism in which part of our knowledge of the world of appearances is guaranteed by the very structures of our understanding. The tension between empiricism and idealism continues to shape philosophical reflection to this day.

6 From the Scientific Revolution to the Twentieth Century

Throughout the eighteenth century and into the nineteenth, scientists and philosophers debated the issue of scientific methodology. Newton's disparaging remarks about "hypotheses" led some of his disciples to take a strong stand against the hypothetico-deductive approach advocated by Christiaan Huygens (1629–1695) and actively pursued on the continent. Advocates of the method of hypothesis saw science as a matter of trying to find plausible guesses that fit existing evidence, then testing those guesses by deriving further consequences to see whether they would continue to hold up; inductivists saw science as a bottom-up activity in which the data from careful experimental work preceded and suggested the theories. The contrast was sometimes drawn more sharply than the actual practice of the scientists would support; Newton himself frequently advanced hypotheses, and Huygens was a careful observer. But the polemical polarization of the two methodological schools had the positive effect of bringing philosophical questions into focus. It is easy, inductivists claimed, to frame a scientific hypothesis to account for all of the available data – so easy that the mere fact one has constructed an empirically adequate hypothesis is no evidence of its truth; but in that case it is a waste of time to construct hypotheses. Their opponents shot back that it is not so easy as all that to come up with even one good hypothesis that fits all of the data and that the mere hoarding up of observations does little to suggest an interesting theory.

The problem of induction, conceived as the problem of determining what, if anything, we are reasonably entitled to infer from an observed uniformity or statistical preponderance, provoked a great deal of thoughtful work but little consensus. Hume's skeptical arguments set the terms of the debate, and John Stuart Mill famously responded that our inductive reasoning depends on the uniformity of nature. The problem became more than academic when uniformity turned out to be the issue in question between two dominant views of geology: catastrophism, represented by Georges Cuvier, and uniformitarianism, championed by James Hutton and Charles Lyell. The problem, in a nutshell, was whether we are entitled to extrapolate backwards in time the sorts and rates of processes we see around us. If so, then various phenomena seem to point to a very old earth; but if we are to believe that catastrophic events of a sort unseen in our time shaped the earth as we find it, such extrapolations may be wide of the mark. Through the course of the nineteenth century, thanks largely to the tireless work of Lyell, the uniformitarians gradually gained the upper hand in this argument.

The first volume of Lyell's *Principles of Geology* appeared in 1830, just in time to be placed in the hands of a young naturalist named Charles Darwin as he set out on a survey expedition aboard HMS *Beagle*. Darwin began to look at rock formations through Lyell's eyes. Geologic "deep time," Darwin reasoned, provided nature with sufficient resources to account for the evolution of species through blind variation and selective retention. The geographic distribution of wildlife seemed inexplicable on a view of special creation. Gradually and cautiously Darwin assembled the evidence for his theory of evolution and finally published it in 1859. A tempestuous public debate ensued and lasted into the early twentieth century when the scientific community was persuaded by the confluence of evidence from geology, paleontology, biology, genetics, astronomy and physics. Biology had found its grand unifying narrative.

The great strength of Darwin's theory is its explanatory power. Around the turn of the twentieth century, philosophers and scientists took a fresh look at the nature of scientific explanation in light of the scientific advances of the preceding three centuries. The American logician and philosopher Charles Sanders Peirce, in particular, gave careful attention to what he called *abduction*, a mode of inference that leads from facts to theories that account for them. Some scientists, including Henri Poincaré, Pierre Duhem, and Albert Einstein, gave serious consideration to the philosophical underpinnings of physical theorizing. Yet they came to no agreement, and their very lack of unanimity posed a puzzle that cried out for resolution. How the logical positivists tried to resolve it, and what became of their solution, is the story told in Part II.

Unit 1

The Ancient and Medieval Periods

From its beginnings in conceptual puzzles regarding motion and the constitution of matter, Greek science developed into a sweeping cosmology and natural philosophy fashioned principally by Aristotle, with the astronomical part brought to maturity by Claudius Ptolemy. The history of science in the Middle Ages is in large part a series of reactions to Aristotle and Ptolemy, including some very critical reactions. Yet the Aristotelian and Ptolemaic view remained dominant through the Middle Ages until the dawn of the scientific revolution.

1 Zeno's Paradoxes

One of the earliest signs of the vitality of Greek thinking about nature was the emergence of puzzles about the fundamental notions of motion, space, and time. In reading 1.3, Zeno of Elea, an older contemporary of Socrates, provides us with some examples in his paradoxes of motion. The paradox of division is typical. In crossing a room, one comes to the halfway point; what remains is half of the distance to be covered. Continuing, one crosses half of that remainder, leaving a quarter of the original distance still to go. We can continue analyzing the situation like this, cutting the remaining distance in half again and again ad infinitum, but no matter how far we go in this analysis there will be some distance left over that is not yet covered. Does this show that one can never cross the room, or more generally that one can never complete the trip from point A to some other point B?

It is hard to say how seriously Zeno took the conclusion that motion is impossible. On the one hand he was a disciple of Parmenides, who held that change is unreal. But on the other hand the conclusion seems so obviously false that it is difficult to imagine anyone's taking it at face value. Whatever Zeno's beliefs, however, his argument requires some sort of answer from those who would maintain the commonsense position that motion is possible.

In the work of Arisotle we have both an account of Zeno's paradoxes and an attempt to resolve them. Aristotle's answer is that both distance (magnitude, or length) and time are potentially infinitely divisible, even though neither a distance nor a time can actually be divided an infinite number of times. For someone moving across the room at a steady rate of speed, the first half of the trip takes half of the time, the next quarter takes a quarter of the time, and so forth. This is true as far as it goes, but Zeno might have responded that Aristotle is still accumulating an infinite number of fractions for the time taken to cover each part of the path:

$$1/2,\ 1/4,\ 1/8,\ \ldots,\ 1/2^n,\ 1/2^{n+1},\ \ldots$$

Each of these fractions is greater than zero, yet for the commonsense position to work the sum of the infinite series must be finite. Modern mathematics is up to the task: one of the classic proofs in undergraduate math shows that the sum of this series is 1. But it was not until the work of Cauchy in the nineteenth century that we possessed a rigorous justification for the summing of an infinite series. Aristotle's response would be rather different: that at any point in the process of dividing a time or a space we have, not an infinite number of these fractions, but a finite number of them.

2 The Atomists

The central insight of Greek science is that the universe is a comprehensible whole and the phenomena around us are governed by rationally discoverable principles. The search for underlying order led some of the Greeks to an astonishing hypothesis: everything we see around us is made of small indivisible components, which they called atoms, and the varied phenomena of nature can be explained in terms of atoms moving in the void, the properties of objects depending on the ordering of the atoms just as the meaning of words and sentences depends on the ordering of letters. Democritus, a contemporary of Socrates, is one of the first writers we know of to advance this position; reading 1.1, from an account preserved in the writings of Diogenes Laertius, gives a brief and tantalizing glimpse of his thought. In reading 1.2, a letter from the atomist philosopher Epicurus to a student named Herodotus, we find a fuller display of the explanatory power of atomism. Reading 1.11, from the Roman poet Lucretius's work *On the Nature of Things*, gives a later and more detailed defense of atomism.

With only atoms and the void, Democritus and his followers attempted to resolve a major conceptual issue that occupied some of the best Greek minds: to give an account of *change*, considered as a general phenomenon. Children are born, grow old, and die; a leaf flourishes and withers; wet clothes hung out on the line dry in the wind; wax left by the fire softens and melts into a puddle; a bird flickers across the space from one tree to another; a ring worn next to the finger grows thin over the course of many years; the sun rises and sets. All of these phenomena exhibit change, yet change with unity: it is in some sense the same leaf that withers, the same wax that melts, the same ring that is gradually worn. According to the atomists, all of the varieties of change could be reduced to one: the change of position of atoms with respect to one another. Like the letters of the alphabet, the atoms could be rearranged to produce different and distinctive entities, and the possibilities for ever more complex combinations of atoms were limitless.

From the outset, the atomist project was profoundly reductive. Democritus explicitly says that the soul itself is composed of atoms, and in Lucretius's hands atomism becomes an argument for atheism. If the effects commonly ascribed to the gods are in fact explicable in natural terms, then the gods are out of a job; we have no need to hypothesize their existence. But the very scope of the project was also a handicap. Atoms were imperceptible, and their reality had to be defended by plausible arguments rather than by demonstrative proofs. Lacking any compelling account of how atoms interact, the early atomists were unable to give a detailed account of how rearrangements of atoms underwrite the spectacular diversity of nature's effects. The existence of a void was also a theoretical postulate, though one supported by an ingenious thought experiment: if there were no void, motion would be impossible since all material things would be caught up in cosmic gridlock, the ultimate traffic jam.

Democritus viewed the cosmos of atoms and void as a deterministic system. Subsequent atomists were not always content or comfortable with this, and some critics found determinism unacceptable or absurd. The metaphysical simplicity of atomism proved to be both a strength and a weakness; a strength, insofar as simplicity is an attractive feature of any theory, but a weakness when it came to giving a detailed account of the wild variety of physical phenomena, particularly since Greek atomism offered no account of the cohesion of atoms. Atomism never died out, but it drifted to the margins of science. There it waited over the centuries until some of its ideas were revived and reformulated by scientists like Galileo, Boyle, and Newton during the scientific revolution.

3 Plato's Cosmology

In reading 1.4 from the *Timaeus*, Plato offers a very different image of the world. In the form of a story he tells of the creation of the universe by a benevolent demiurge who strives, with mixed success, to represent in a physical medium the structure of the eternal Forms. Mathematical ideas dominate the story. There are four elements, earth, air, fire, and water, each with its distinctive properties. Why four? Plato conjectures – he makes it plain, through the mouth of the character Timaeus, that he is not pretending to deduce all of this with certainty but only to tell a "likely tale" – that the four elements may correspond to four of the regular convex solids: fire to the tetrahedron, earth to the cube, air to the octahedron, water to the icosahedron. (Another mathematical argument Plato offers for there being four elements is that between any two cubes, a^3 and b^3, there are two other terms that fill in a geometrical progression, a^2b and ab^2.) Each of these solids has sides that can be disassembled into triangles and then reassembled, permitting in principle the transformation of one element into another. There is in addition a fifth solid, the dodecahedron, which has twelve pentagonal faces. Plato suggests that this may correspond to the quintessence of which the heavens themselves are made. Celestial motions are dictated by the mathematical analysis of the musical scale. The universe is spherical, as are the individual stars, and the system taken together is "an intricately wrought whole."

Plato was well aware that there were details not yet accounted for by the sort of system he favored. In Book 10 of the *Republic* he makes a passing reference to the retrograde motion of Mars (see Figure 1), and he gave his pupils in the Academy the task of creating a model that would more accurately reflect the visible motions of the planets and bring their seemingly capricious reversals under the control of an overarching mathematical ideal. One of those students, Eudoxus, refined Plato's model by employing 27 spheres and allowing the axes of each sphere to be attached to the next at an angle. By means of this ingenious construction, Eudoxus was able to reproduce, at least qualitatively, the retrograde motions of the planets.

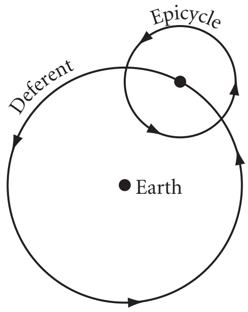

Figure 1 The epicycle. The planet travels on the rotating epicycle, which is itself carried around the deferent. By selecting the rotational speeds and the radius of the epicycle carefully, one can reproduce the retrograde motion of a planet as it is seen from earth (from W. T. Sedgwick and H. W. Tyler, *A Short History of Science* [New York: Macmillan, 1917], p. 118)

The goal of "saving the appearances" – of giving an account that squares with the visible phenomena – is still with us as a part of modern science, and in the eyes of some contemporary empiricists like van Fraassen it is the principal goal of science. But Plato's emphasis on mathematics came at the expense of a detailed study of the physical world, and this left him and his students at a disadvantage when it came to the study of complex phenomena. The patterns of stellar and planetary motion are, all things considered, among the simplest of natural phenomena and the most amenable to mathematical description. In contrast, the mathematical analysis of biological phenomena is a problem so much more difficult, and requiring so much more information than the Greeks could have obtained with the unaided eye, that Plato had nothing interesting to say on the subject. It was Plato's greatest pupil, Aristotle, who articulated a radically different view of nature that opened the way to intelligible explanations of more complicated phenomena.

4 Aristotle's Natural Philosophy

No other figure in history has ever dominated the intellectual landscape in as many fields as Aristotle. His views were almost always the point of departure for a discussion of any scientific topic; for the better part of two millennia, the accepted method of making a contribution to scientific thought was to write a commentary on one of Aristotle's scientific works. Many of his works were lost to the west in the early Middle Ages, but in the Arab world the tradition of commentary on Aristotle continued. During the eleventh century Aristotle's works returned to the west, first in translations from Arabic to Latin and later directly from Greek into Latin, and the most prominent scholars of the high Middle Ages discussed them vigorously. At the Council of Trent in the mid 1500s Aristotle was designated by the Catholic Church as the preeminent authority in matters of philosophy.

Aristotle's sweeping synthesis offered an impressively unified view of logic, metaphysics, epistemology, biology, physics, and astronomy. Aristotle did not build this system entirely from scratch, but his thorough review of prior theories and his ingenious and interconnected resolutions to existing problems gave his views substance and authority. When it was needed, as reading 1.6 shows, he would ask and then answer the simple but deep questions that provide the framework for scientific reasoning, questions about the fundamental constituents of nature, the sorts of causes, and the conceptual relations of necessity, spontaneity, and chance. In reading 1.9 he extends the same sort of care to the fundamental questions about living things, asking how they differ from abstract objects, what sorts of causes are appropriate to inquiry about the living world, and the method of grasping the real causes of things. The method of classification he proposes, based on looking at the similarities and differences of things, is the foundation of comparative morphology; it was the principle that undergirded the dominant taxonomic scheme (kingdom, phylum, class, order . . .) until the advent of molecular genetics.

But he could also engage in system building on the grandest scale. Noting the unchanging nature of the heavens and the mutable nature of the earth and its nearby atmosphere, Aristotle makes a fundamental cut between the celestial and terrestrial realms and constructs distinct sets of fundamental principles to govern each. He addresses the problem of change through a distinction between form and matter and an analysis of four senses in which we might say that one thing causes another. He answers the question of which sorts of changes require explanation and which do not by laying down the doctrine of essential natures and natural motions.

The notion of essential natures is foreign to our present view of science, but it is critical to the Aristotelian system. Each natural object, according to Aristotle, belongs to a kind, and objects of each kind have a nature that determines how they behave naturally, that is, when not acted upon by other objects. It is the nature of a seed to grow into a plant, but it is not the nature of a seed to move across the landscape; for that, it must be blown along by the wind or caught on the flank of a passing animal. By appealing to the essential natures of kinds of things, which is to say, their natural ends, Aristotle could widen the scope of science to include all natural phenomena and make a principled distinction between events or sorts of behavior that require explanation and events that do not. When things behave according to their natures, no explanation is required; when they do not, we must seek an explanation. True scientific knowledge, Aristotle argues in reading 1.7, consists in demonstration from a knowledge of the essential natures of things.

Another way of expressing this same thought is that each natural object has a *telos* – a goal or an end which it has an intrinsic tendency to reach. An acorn's *telos* is an oak tree; or, to use the term a bit more freely, we might say that its *telos* is its tendency to become an oak tree. This teleological conception of nature shapes the explanations Aristotle offers: we can rest content with an explanation when we have traced the behavior of an object back to an understanding of its *telos*.

The appeal to natures is evident in Aristotle's account of free fall. All mundane physical objects are either heavy or light, depending on which elements preponderate in their makeup. A heavy object such as a stone will fall naturally downward, that is, toward the center of the universe, where the center of the spherical earth is located. The stone will continue to fall even through a medium thicker than air, such as water or honey, but its rate of fall is slowed considerably. Though he does not use a mathematical formula to express his views, Aristotle gives enough verbal description of the relationship between force and resistance to suggest that he accepted, within certain limits, the idea that velocity is directly proportional to force and inversely proportional to resistance, or $V \propto F/R$. This view of the relation of these variables has an interesting consequence: in the limit as resistance goes to zero, the velocity of an object acted upon by even the slightest force goes to infinity. Aristotle quite reasonably objected that infinite velocity is an absurdity; an object moving at an infinite velocity would literally be in two places at the same time. Therefore there must always be some resistance – and hence, contrary to the atomists, there cannot be a void.

Aristotle's cosmology exhibits some of the central features of his scientific thought. In reading 1.5, he takes up the question of the motions of the stars and the planets. The stars wheel around us every 24 hours, but the planets gradually work their way through the band of constellations that make up the ecliptic, and they do so in irregular ways. All of these motions require a cause, that is, something in contact with the thing moved that keeps it moving. Aristotle develops a famous argument that the regress of causes cannot go on to infinity: there must be something that moves without itself being moved. In reading 1.8, Aristotle gives us more details about the large-scale structure of the universe and the shape and size of the earth. Contrary to a nineteenth-century urban legend that the medievals believed in a flat earth, virtually every educated person from the time of Aristotle onward realized that the earth is approximately spherical.[1]

Although Aristotle was a plenist – that is, he denied that there is any void or vacuum anywhere in nature – he understood the appeal of the gridlock argument advanced by the atomists. He countered it with a circulatory theory of motion called *antiperistasis* according to which adjacent objects could move in a circle, or at least in a closed curve, like a long line of train cars on a circular track with the engine coming around to touch the caboose from behind. Formally, the solution was adequate: objects could move this way in a plenum without gridlock. Its merits as an explanation of motion were less obvious. Aristotle suggests with some hesitancy that the continued motion of a flung stone may be due to the rush of displaced air around behind it, pushing it onward.

Aristotle conceived of science as knowledge of reasoned facts deduced from evident first principles. The distinction between knowledge of facts and knowledge of reasoned facts is significant. In a passage from the *Posterior Analytics* I.13 illustrating the distinction, Aristotle considers the planets, which we know from observation do not twinkle as the stars do but rather shine with a steady light. Why is this? Aristotle's answer is that they are relatively near, and that which is near does not twinkle. Here we have not only a demonstration but a causal explanation for the observed phenomenon, a paradigm case of knowledge of the reasoned fact. But how do we know that the planets are close? We can construct another argument using the same basic materials: what does not twinkle is relatively near, and the planets do not twinkle; therefore, they are relatively near. This second argument, however, does not give us an *explanation* of the nearness of the planets. Here, in Aristotle's terms, we have knowledge of the fact but not of the reasoned fact.

This example, however, raises more problems than it resolves. The ultimate starting points for scientific demonstration must, according to Aristotle, be known with certainty. But how can we know with certainty the critical premise that what is near does not twinkle? Accidental correlation of nearness with non-twinkling will not do the job; non-twinkling must be an essential characteristic of nearby objects or an essential consequence of their nearness. For that matter, how can we know that the correlation invariably holds? These two problems – the problem of distinguishing generalizations that hold necessarily or essentially from accidentally true ones, and the problem of inferring universal generalizations, even accidental ones, from mere instances of correlation – cast a long shadow over the philosophy of science, resurfacing time and again up through the twentieth century.

5 Ptolemaic Astronomy

In the second century AD, Claudius Ptolemy synthesized Aristotelian ideas regarding motion with a great mass of observational data and considerable geometric ingenuity to produce the definitive work on positional astronomy. Ptolemy's tome, best known by its Arabic title *Almagest*, is a curious and difficult book. His stated aim is to construct a positional astronomy that will yield predictions in good agreement with observation, to "save the phenomena." Three critical conclusions for which he argues in the first book (reading 1.12)

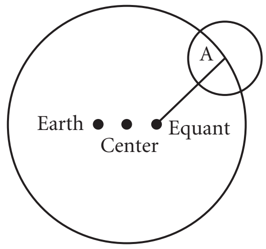

Figure 2 The equant. The planet travels on the epicycle with center A. The line from the equant to A rotates at a constant speed. But this means that the speed of A around the deferent, viewed either from earth or from the center of the circle, will not be constant (from W. T. Sedgwick and H. W. Tyler, *A Short History of Science* [New York: Macmillan, 1917], p. 130)

are that the earth is spherical, that its size in comparison with the distance to the stars is negligible, and that it does not move.

Ptolemy's argument that the earth is motionless provides a good illustration of his use of Aristotle. The fundamental principle of forced (unnatural) motion, according to Aristotle, is that everything that moves unnaturally is moved by something else. Suppose, then, that the earth rotates on its axis once every twenty-four hours. An observer whose feet are planted firmly on the ground is moved by, and therefore moves with, the earth. But if he jumps, his feet lose contact with the earth; and therefore, according to Aristotle, he should no longer move with it. If we take Aristotle's dynamics seriously, we should expect anyone who jumps up into the air to be slammed into the west wall of the room at speeds up to 1000 miles per hour (depending on the latitude of the unfortunate jumper). Obviously this does not happen. Ptolemy, who takes Aristotle's dynamics very seriously, draws the conclusion that the earth is not rotating.

But Ptolemy takes liberties with Aristotle whenever doing so increases his predictive accuracy, and he shows a shocking lack of concern for the consistency of his geometric constructions with one another. His constructions, compounded of little circles (called *epicycles*) that ride on other circles (called *deferents*), with the heavenly bodies riding on the epicycles, provide a tolerably good guide to the apparent positions of the planets in the night sky (see Figure 2). In particular, by a careful combination of motions – the planet moving on the epicycle at one speed, the epicycle moving on the deferent at another – Ptolemy is able to reproduce the periodic retrograde motions of the planets. But the selection of radii for these circles are in many cases arbitrary – other sizes of radius might do equally well – and in some cases (e.g. with the moon) there is no three-dimensional path through space that corresponds to all of Ptolemy's constructions, since he uses one radius for the computation of the moon's visible size and a different one for its motion. One can build scale models of pieces of the Ptolemaic system, but one cannot build a single scale model that represents all of the incompatible pieces.

Is this a problem? The answer depends very much on one's view of the aims of science, and of astronomy in particular. If the geometric models of Ptolemaic astronomy are considered as mere calculating devices, they do their job well enough. His system as a whole is a reasonably accurate predictive instrument, and if prediction is all we ask from a theory, we have little ground for complaint. But if we want a believable picture of the paths of the planets through three-dimensional space or an account of the causes of their motions, Ptolemy's account in the *Almagest* does not offer what we seek. Even waiving the problem of incompatible constructions, his system invokes many strange and implausible devices. Planets ride on epicycles while the centers of those epicycles travel along deferents, yet the center of every circle involved is not a heavenly body – even the earth is not quite at the geometric center of Ptolemy's solar system – but an empty point in space. And the rotational speeds of these circles are not always uniform in the sense Aristotle intended; in multiple cases a point moving along the circumference of the deferent sweeps out equal angles in equal times only when viewed from the *equant*, a point other than the center of the deferent (see Figure 3).

6 The Critical Reaction to Aristotle and Ptolemy

Some casual observers of the history of science have mistaken the apparent obsession of medieval

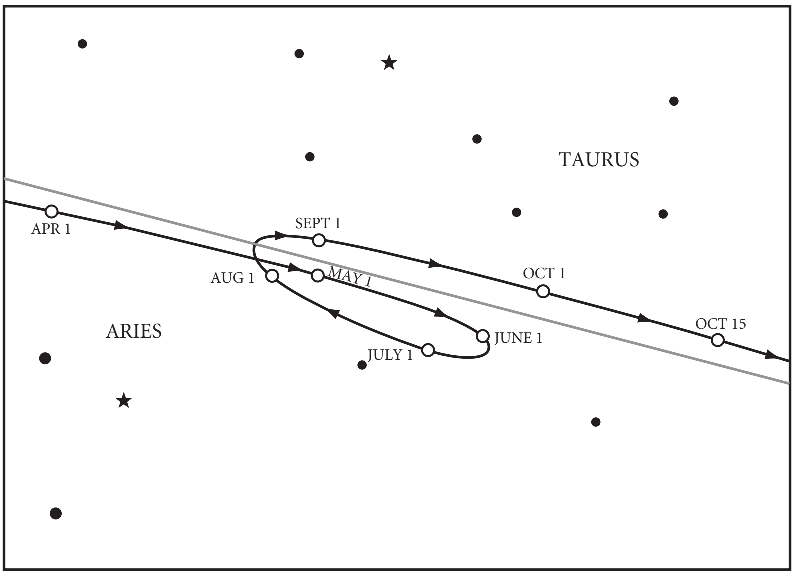

Figure 3 Retrograde motion. The diagram shows the apparent path of Mars through the constellations Aries and Taurus during a six-month period. Starting in mid June the planet stops, reverses its course, stops again, and finally heads back in the original direction (from Kuhn, *The Copernican Revolution* [Cambridge, MA: Harvard University Press, 1957], p. 48, figure 15)

thinkers with Aristotle for blind, uncritical acceptance of his teachings. This misconception, like the myth that the medievals believed in a flat earth, was a Victorian invention, and it still works its way into textbooks and popular essays despite the best efforts of professional historians of science. Many of the commentaries on Aristotle are quite critical. Some offer experimental evidence for or against his views, particularly his views on motion, and against Ptolemy's astronomy.

We can get a glimpse of dissatisfaction with the Aristotelian conception of science in a fragment from the writings of Philodemus, an Epicurean philosopher writing in the first century BC (reading 1.10). Philodemus is concerned with the discovery of essential characteristics, and he stresses the importance of having a wide sample and varying the other characteristics. Though Philodemus's immediate target is the Stoic position, the methodological precautions he advocates are pointless on the Aristotelian view. If the abstraction of essences is the ineffable operation of *nous*, or the mind, there is no need for large and varied samples.

In the sixth century, the Christian philosopher John Philoponus offered more direct and vigorous criticisms of Aristotle's physical theories. Aristotle's suggested account of projectile motion, Philoponus argues in reading 1.14, is not credible; various everyday experiences and easily constructed experiments show it to be false. But if the air is not pushing the flung object, why does it continue to move? Philoponus advances a novel solution: the hand imparts to the object an *impetus*, an internal force or tendency to motion, and that impetus then carries the object along after it is released from the hand. From a modern perspective this is wrong, but it is in an important sense less wrong than Aristotle's original conception. It is not an accident that Galileo adopted the theory of impetus in his youth before he developed his more powerful and more nearly accurate concept of inertia – which he still calls "impetus" – in the *Dialogue Concerning the Two Chief Systems of the World* in 1632.

The Aristotelian position on free fall fares no better at Philoponus's hands (reading 1.15). Though he agrees with Aristotle that there is in fact no void, Philoponus thinks this is not a matter of necessity; since it follows from Aristotle's analysis of velocity in terms of force and resistance, that analysis must be wrong. Philoponus's position can, to a first approximation, be expressed in a modern notation as $V \propto F - R$. One consequence of this is that motion in the absence of resistance need not be infinitely swift. Again, although from a modern standpoint this analysis is still misguided, it represents a step forward in the analysis of motion.

Ptolemy also comes in for his share of criticism. In reading 1.13, the Neoplatonic philosopher Proclus, writing in the fifth century, expresses dismay at the "casual attitude" of the astronomers in expounding the hypothetical devices they use to account for planetary motions. Significantly, he stresses that mere successful prediction does not satisfy our yearning for complete understanding, for the real explanations behind the mathematical constructions.

These aspects of Ptolemy's system in the *Almagest* bothered subsequent thinkers. Toward the end of the twelfth century, the Jewish thinker Maimonides echoed Proclus's complaints (reading 1.16). Yet Maimonides is genuinely perplexed as to how to account for retrograde motion without the use of epicycles. By the fourteenth century, dissatisfaction with Ptolemy's astronomy was well entrenched in Paris. Both Jean Buridan (1.17) and his brilliant student Nicole Oresme (1.18) openly discussed the compatibility of the earth's rotation with astronomical data, even suggesting modifications to Aristotle's physics in order to reconcile the conjecture with observation.

All of these arguments were extant in the literature; many of them were available to subsequent generations of thinkers, at least those who lived near centers of learning. But in the absence of some better system of comparable scope, Aristotle's view of science and the Ptolemaic model of the heavens remained dominant. The questions and alternative proposals of the critics remained scattered across the intellectual landscape until they were drawn together in the scientific revolution.

Note

1 The chief perpetrator of this urban legend was Washington Irving, better known as the author of "The Legend of Sleepy Hollow." See Jeffrey Burton Russell, *Inventing the Flat Earth* (New York: Praeger, 1997).

Suggestions for Further Reading

The following brief list offers a sampling of the rich literature in the history of science pertaining to the material covered in Unit 1. Items marked with an asterisk assume little or no background in the subject; these would be a good place to begin further reading.

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1.1

Atoms and Empty Space

Diogenes Laertius

Democritus (c.460–c.370 BC), a student of Leucippus, gave the first clear and widely read expression of atomism. Though we no longer have any complete works by Democritus, the following summary of his teachings on atoms and the void is preserved in the ninth volume of Diogenes Laertius' *Lives of the Philosophers*, a work probably written in the third century AD Diogenes reports a good deal of gossip about the philosophers he discusses, not all of it reliable. He attributes to Aristoxenus the claim that Plato wanted to burn all of the available copies of Democritus' numerous works.

The first principles of the universe are atoms and empty space. Everything else is merely thought to exist. The worlds are unlimited [or boundless]. They come into being and perish. Nothing can come into being from that which is not nor pass away into that which is not. Further, the atoms are unlimited in size and number, and they are borne along in the whole universe in a vortex, and thereby generate all composite things – fire, water, air, earth. For even these are conglomerations of given atoms. And it is because of their solidity that these atoms are impassive and unalterable. The sun and the moon have been composed of such smooth and spherical masses [i.e., atoms], and so also the soul, which is identical with reason.

In *The Book of the Cosmos*, ed. Dennis Richard Danielson (Cambridge, MA: Perseus, 2000), p. 25.

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1.2

Letter to Herodotus

Epicurus

Epicurus (c.341–c.271 BC) was an articulate spokesman for atomism. We are indebted again to Diogenes Laertius for preserving, in the tenth book of his *Lives of the Philosophers*, a considerable amount of Epicurus' own work, including the letter to Herodotus (not to be confused with the historian by the same name) from which the following selection is taken. In this letter Epicurus summarizes his atomism and sketches the way that it can be employed to account for observable phenomena.

Epicurus to Herodotus, greeting.

For those who are unable to study carefully all my physical writings or to go into the longer treatises at all, I have myself prepared an epitome of the whole system, Herodotus, to preserve in the memory enough of the principal doctrines, to the end that on every occasion they may be able to aid themselves on the most important points, so far as they take up the study of physics. . . .

To begin with, nothing comes into being out of what is non-existent. For in that case anything would have arisen out of anything, standing as it would in no need of its proper germs. And if that which disappears had been destroyed and become nonexistent, everything would have perished, that into which the things were dissolved being nonexistent. Moreover, the sum total of things was always such as it is now, and such it will ever remain. For there is nothing into which it can change. For outside the sum of things there is nothing which could enter into it and bring about the change.

Further, the whole of being consists of bodies and space. For the existence of bodies is everywhere attested by sense itself, and it is upon sensation that reason must rely when it attempts to infer the unknown from the known. And if there were no space (which we call also void and place and intangible nature), bodies would have nothing in which to be and through which to move, as they are plainly seen to move. Beyond bodies

In *The Book of the Cosmos*, ed. Dennis Richard Danielson (Cambridge, MA: Perseus, 2000), pp. 25–7.

and space there is nothing which by mental apprehension or on its analogy we can conceive to exist. When we speak of bodies and space, both are regarded as wholes or separate things, not as the properties or accidents of separate things.

Again, of bodies some are composite, others the elements of which these composite bodies are made. These elements are indivisible ["*atoma*"] and unchangeable, and necessarily so, if things are not all to be destroyed and pass into non-existence, but are to be strong enough to endure when the composite bodies are broken up, because they possess a solid nature and are incapable of being anywhere or anyhow dissolved. It follows that the first beginnings must be indivisible, corporeal entities.

Again, the sum of things is infinite [or boundless]. For what is finite has an extremity, and the extremity of anything is discerned only by comparison with something else. Now the sum of things is not discerned by comparison with anything else. Hence, since it has no extremity, it has no limit. And since it has no limit, it must be unlimited or infinite.

Moreover, the sum of things is unlimited both by reason of the multitude of the atoms and the extent of the void. For if the void were infinite and bodies finite, the bodies would not have stayed anywhere but would have been dispersed in their course through the infinite void, not having any supports or counter-checks to send them back on their upward rebound. Again, if the void were finite, the infinity of bodies would not have anywhere to be.

Furthermore, the atoms, which have no void in them – out of which composite bodies arise and into which they are dissolved – vary indefinitely in their shapes. For so many varieties of things as we see could never have arisen out of a recurrence of a definite number of the same shapes. The like atoms of each shape are absolutely infinite. But the variety of shapes, though indefinitely large, is not absolutely infinite.

The atoms are in continual motion through all eternity.

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1.3

The Paradoxes of Motion

Plato

Zeno of Elea (c.490–c.430 BC) was a native of southern Italy and a disciple of Parmenides. His fame rests entirely on four paradoxes recounted here by Aristotle in his *Physics*. The paradoxes seem silly if taken literally, as their conclusions contradict the evidence of the senses; they are better understood as shrewd challenges to the adequacy of existing concepts of space, time, and motion. Obviously something goes wrong in the reasoning presented in each case. But what is it? A satisfactory answer did not emerge until the development of the calculus in the seventeenth century.

[. . .]

Moreover, the current arguments make it plain that, if time is continuous, magnitude is continuous also, inasmuch as a thing passes over half a given magnitude in half the time, and in general over a less magnitude in less time; for the divisions of time and of magnitude will be the same. And if either is infinite, so is the other, and the one is so in the same way as the other; i.e. if time is infinite in respect of its extremities, length is also infinite in respect of its extremities; if time is infinite in respect of divisibility, length is also infinite in respect of divisibility; and if time is infinite in both respects, magnitude is also infinite in both respects.

Hence Zeno's argument makes a false assumption in asserting that it is impossible for a thing to pass over or severally to come in contact with infinite things in a finite time. For there are two ways in which length and time and generally anything continuous are called infinite: they are called so either in respect of divisibility or in respect of their extremities. So while a thing in a finite time cannot come in contact with things quantitatively infinite, it can come in contact with things infinite in respect of divisibility; for in this sense the time itself is also infinite: and so

From *The Complete Works of Aristotle*, ed. Jonathan Barnes, Vol. 1 (Princeton, NJ: Princeton University Press, 1984), extracts from pp. 393–4, 404–5, 439 ("Physics V and VIII").

we find that the time occupied by the passage over the infinite is not a finite but an infinite time, and the contact with the infinites is made by means of moments not finite but infinite in number.

[. . .]

Zeno's arguments about motion, which cause so much trouble to those who try to answer them, are four in number. The first asserts the non-existence of motion on the ground that that which is in locomotion must arrive at the half-way stage before it arrives at the goal. This we have discussed above.

The second is the so-called Achilles, and it amounts to this, that in a race the quickest runner can never overtake the slowest, since the pursuer must first reach the point whence the pursued started, so that the slower must always hold a lead. This argument is the same in principle as that which depends on bisection, though it differs from it in that the spaces with which we have successively to deal are not divided into halves. The result of the argument is that the slower is not overtaken; but it proceeds along the same lines as the bisection-argument (for in both a division of the space in a certain way leads to the result that the goal is not reached, though the Achilles goes further in that it affirms that even the runner most famed for his speed must fail in his pursuit of the slowest), so that the solution too must be the same. And the claim that that which holds a lead is never overtaken is false: it is not overtaken while it holds a lead; but it is overtaken nevertheless if it is granted that it traverses the finite distance. These then are two of his arguments.

The third is that already given above, to the effect that the flying arrow is at rest, which result follows from the assumption that time is composed of moments: if this assumption is not granted, the conclusion will not follow.

The fourth argument is that concerning equal bodies which move alongside equal bodies in the stadium from opposite directions – the ones from the end of the stadium, the others from the middle – at equal speeds, in which he thinks it follows that half the time is equal to its double. The fallacy consists in requiring that a body travelling at an equal speed travels for an equal time past a moving body and a body of the same size at rest. That is false. E.g. let the stationary equal bodies be AA; let BB be those starting from the middle of the A's (equal in number and in magnitude to them); and let CC be those starting from the end (equal in number and magnitude to them, and equal in speed to the B's). Now it follows that the first B and the first C are at the end at the same time, as they are moving past one another. And it follows that the C has passed all the A's and the B half; so that the time is half, for each of the two is alongside each for an equal time. And at the same time it follows that the first B has passed all the C's. For at the same time the first B and the first C will be at opposite ends,* being an equal time alongside each of the B's as alongside each of the A's, as he says,* because both are an equal time alongside the A's. That is the argument, and it rests on the stated falsity.

[. . .]

But, although this solution is adequate as a reply to the questioner (the question asked being whether it is impossible in a finite time to traverse or count an infinite number of units), nevertheless as an account of the fact and the truth it is inadequate. For suppose the distance to be left out of account and the question asked to be no longer whether it is possible in a finite time to traverse an infinite number of distances, and suppose that the inquiry is made to refer to the time itself (for the time contains an infinite number of divisions): then this solution will no longer be adequate, and we must apply the truth that we enunciated in our recent discussion.

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1.4

Plato's Cosmology

Plato

Plato (427–347 BC) was a pupil of Socrates and the teacher of Aristotle. His dialogues exerted a tremendous influence on the development of most of the major areas of philosophy. This selection from the *Timaeus* presents a speculative creation myth that gives a sense of both the nature and the limitations of Plato's cosmology. His treatment of space and his description of the nature and interactions of the four elements provide a striking contrast to the notions of Democritus, and his account of the composition of bodies by triangles reveals his profoundly geometric, a priori turn of mind. Yet he seems conscious of the limitation of this method, since he leaves open the possibility that there may be "principles yet more ultimate than these."

Now as to the whole universe or world order [*kosmos*] – let's just call it by whatever name is most acceptable in a given context – there is a question we need to consider first. This is the sort of question one should begin with in inquiring into any subject. Has it always existed? Was there no origin from which it came to be? Or did it come to be and take its start from some origin? It has come to be. For it is both visible and tangible and it has a body – and all things of that kind are perceptible. And, as we have shown, perceptible things are grasped by opinion, which involves sense perception. As such, they are things that come to be, things that are begotten. Further, we maintain that, necessarily, that which comes to be must come to be by the agency of some cause. Now to find the maker and father of this universe [*to pan*] is hard enough, and even if I succeeded, to declare him to everyone is impossible. And so we must go back and raise this question about the universe: Which of the two models did the maker use when he fashioned it? Was it the one that does not change and stays the same, or the one that has come to be? Well, if this world of ours is beautiful and its craftsman good, then clearly he looked at the eternal model. But if

From *Timaeus*, trans. by Donald Zeyl (Hackett, 2000), pp. 14–15, 17–18, 23–5, 26–7, 39–40, 42–3.

what it's blasphemous to even say is the case, then he looked at one that has come to be. Now surely it's clear to all that it was the eternal model he looked at, for, of all the things that have come to be, our universe is the most beautiful, and of causes the craftsman is the most excellent. This, then, is how it has come to be: it is a work of craft, modeled after that which is changeless and is grasped by a rational account, that is, by wisdom.

Since these things are so, it follows by unquestionable necessity that this world is an image of something. Now in every subject it is of utmost importance to begin at the natural beginning, and so, on the subject of an image and its model, we must make the following specification: the accounts we give of things have the same character as the subjects they set forth. So accounts of what is stable and fixed and transparent to understanding are themselves stable and unshifting. We must do our very best to make these accounts as irrefutable and invincible as any account may be. On the other hand, accounts we give of that which has been formed to be like that reality, since they are accounts of what is a likeness, are themselves likely, and stand in proportion to the previous accounts, i.e., what being is to becoming, truth is to convincingness. Don't be surprised then, Socrates, if it turns out repeatedly that we won't be able to produce accounts on a great many subjects – on gods or the coming to be of the universe – that are completely and perfectly consistent and accurate. Instead, if we can come up with accounts no less likely than any, we ought to be content, keeping in mind that both I, the speaker, and you, the judges, are only human. So we should accept the likely tale on these matters. It behooves us not to look for anything beyond this.

[. . .]

Now that which comes to be must have bodily form, and be both visible and tangible, but nothing could ever become visible apart from fire, nor tangible without something solid, nor solid without earth. That is why, as he began to put the body of the universe together, the god came to make it out of fire and earth. But it isn't possible to combine two things well all by themselves, without a third; there has to be some bond between the two that unites them. Now the best bond is one that really and truly makes a unity of itself together with the things bonded by it, and this in the nature of things is best accomplished by proportion. For whenever of three numbers which are either solids or squares the middle term between any two of them is such that what the first term is to it, it is to the last, and, conversely, what the last term is to the middle, it is to the first, then, since the middle term turns out to be both first and last, and the last and the first likewise both turn out to be middle terms, they will all of necessity turn out to have the same relationship to each other, and, given this, will all be unified.

So if the body of the universe were to have come to be as a two dimensional plane, a single middle term would have sufficed to bind together its conjoining terms with itself. As it was, however, the universe was to be a solid, and solids are never joined together by just one middle term but always by two. Hence the god set water and air between fire and earth, and made them as proportionate to one another as was possible, so that what fire is to air, air is to water, and what air is to water, water is to earth. He then bound them together and thus he constructed the visible, and tangible universe. This is the reason why these four particular constituents were used to beget the body of the world, making it a symphony of proportion. They bestowed friendship upon it, so that, having come together into a unity with itself, it could not be undone by anyone but the one who had bound it together.

Now each one of the four constituents was entirely used up in the process of building the world. The builder built it from all the fire, water, air and earth there was, and left no part or power of any of them out. His intentions in so doing were these: First, that as a living thing it should be as whole and complete as possible and made up of complete parts. Second, that it should be just one universe, in that nothing would be left over from which another one just like it could be made. Third, that it should not get old and diseased. He realized that when heat or cold or anything else that possesses strong powers surrounds a composite body from outside and attacks it, it destroys that body prematurely, brings disease and old age upon it and so causes it to waste away. That is why he concluded that he should fashion the world as a single whole, composed of all wholes, complete and free of old age and disease, and why he fashioned it that way. And he gave it a shape appropriate to the kind of thing it was. The appropriate shape for that living thing that is to contain within itself all the living things would be the one which embraces within itself all the shapes there are. Hence he gave it a round shape, the form of a sphere, with its center equidistant from its extremes in all directions. This of all shapes is the most complete and most like itself, which he gave to it because he believed that likeness is incalculably more excellent than unlikeness.

[. . .]

Now when the Father who had begotten the universe observed it set in motion and alive, a thing that had come to be as a shrine for the everlasting gods, he was well pleased, and in his delight he thought of making it more like its model still. So, as the model was itself an everlasting Living Thing, he set himself to bringing this universe to completion in such a way that it, too, would have that character to the extent that was possible. Now it was the Living Thing's nature to be eternal, but it isn't possible to bestow eternity fully upon anything that is begotten. And so he began to think of making a moving image of eternity: at the same time as he brought order to the universe, he would make an eternal image, moving according to number, of eternity remaining in unity. This number, of course, is what we now call "time."

For before the heavens came to be, there were no days or nights, no months or years. But now, at the same time as he framed the heavens, he devised their coming to be. These all are parts of time, and *was* and *will be* are forms of time that have come to be. Such notions we unthinkingly but incorrectly apply to everlasting being. For we say that it *was* and *is* and *will be*, but according to the true account only *is* is appropriately said of it. *Was* and *will be* are properly said about the becoming that passes in time, for these two are motions. But that which is always changeless and motionless cannot become either older or younger in the course of time – it neither ever became so, nor is it now such that it has become so, nor will it ever be so in the future. And all in all, none of the characteristics that becoming has bestowed upon the things that are borne about in the realm of perception are appropriate to it. These, rather, are forms of time that have come to be – time that imitates eternity and circles according to number. And what is more, we also say things like these: that what has come to be *is* what has come to be, that what is coming to be *is* what is coming to be, and also that what will come to be *is* what will come to be, and that what is not *is* what is not. None of these expressions of ours is accurate. But I don't suppose this is a good time right now to be too meticulous about these matters.

Time, then, came to be together with the universe so that just as they were begotten together, they might also be undone together, should there ever be an undoing of them. And it came to be after the model of that which is sempiternal, so that it might be as much like its model as possible. For the model is something that has being for all eternity, while it, on the other hand, has been, is, and shall be for all time, forevermore. Such was the reason, then, such the god's design for the coming to be of time, that he brought into being the Sun, the Moon and five other stars, for the begetting of time. These are called "wanderers," and they came to be in order to set limits to and stand guard over the numbers of time. When the god had finished making a body for each of them, he placed them into the orbits traced by the period of the Different – seven bodies in seven orbits. He set the Moon in the first circle, around the earth, and the Sun in the second, above it. The Dawnbearer (the Morning Star, or Venus) and the star said to be sacred to Hermes (Mercury) he set to run in circles that equal the Sun's in speed, though they received the power contrary to its power. As a result, the Sun, the star of Hermes and the Dawnbearer alike overtake and are overtaken by one another. As for the other bodies, if I were to spell out where he situated them, and all his reasons for doing so, my account, already a digression, would make more work than its purpose calls for. Perhaps later on we could at our leisure give this subject the exposition it deserves.

[. . .]

The gods he made mostly out of fire, to be the brightest and fairest to the eye. He made them wellrounded, to resemble the universe, and placed them in the wisdom of the dominant circle [i.e., of the Same], to follow the course of the universe. He spread the gods throughout the whole heaven to be a true adornment [*kosmos*] for it, an intricately wrought whole. And he bestowed two movements upon each of them. The first was rotation, an unvarying movement in the same place, by which the god would always think the same thoughts about the same things. The other was revolution, a forward motion under the dominance of the circular carrying movement of the Same and uniform. With respect to the other five motions, the gods are immobile and stationary, in order that each of them may come as close as possible to attaining perfection.

This, then, was the reason why all those everlasting and unwandering stars – divine living things which stay fixed by revolving without variation in the same place – came to be. Those that have turnings and thus wander in that sort of way came to be as previously described.

[. . .]

[. . .] Suppose you were molding gold into every shape there is, going on non-stop remolding one shape into the next. If someone then were to point at one of them and ask you, "What *is* it?," your safest answer by far, with respect to truth, would be to say, "gold," but never "triangle" or any of the other shapes that come to be in the gold, as though it *is* these, because they change even while you're making the statement. However, that answer, too, should be satisfactory, as long as the shapes are willing to accept "what is such" as someone's designation. This has a degree of safety.

Now the same account, in fact, holds also for that nature which receives all the bodies. We must always refer to it by the same term, for it does not depart from its own character in any way. Not only does it always receive all things, it has never in any way whatever taken on any characteristic similar to any of the things that enter it. Its nature is to be available for anything to make its impression upon, and it is modified, shaped and reshaped by the things that enter it. These are the things that make it appear different at different times. The things that enter and leave it are imitations of those things that always are, imprinted after their likeness in a marvellous way that is hard to describe. This is something we shall pursue at another time. For the moment, we need to keep in mind three types of things: that which comes to be, that in which it comes to be, and that after which the thing coming to be is modeled, and which is the source of its coming to be. It is in fact appropriate to compare the receiving thing to a mother, the source to a father, and the nature between them to their offspring. We also must understand that if the imprints are to be varied, with all the varieties there to see, this thing upon which the imprints are to be formed could not be well prepared for that role if it were not itself devoid of any of those characters that it is to receive from elsewhere. For if it resembled any of the things that enter it, it could not successfully copy their opposites or things of a totally different nature whenever it were to receive them. It would be showing its own face as well. This is why the thing that is to receive in itself all the elemental kinds must be totally devoid of any characteristics. Think of people who make fragrant ointments. They expend skill and ingenuity to come up with something just like this [i.e., a neutral base], to have on hand to start with. The liquids that are to receive the fragrances they make as odorless as possible. Or think of people who work at impressing shapes upon soft materials. They emphatically refuse to allow any such material to already have some definite shape. Instead, they'll even it out and make it as smooth as it can be. In the same way, then, if the thing that is to receive repeatedly throughout its whole self the likenesses of the intelligible objects, the things which always are – if it is to do so successfully, then it ought to be devoid of any inherent characteristics of its own. This, of course, is the reason why we shouldn't call the mother or receptacle of what has come to be, of what is visible or perceivable in every other way, either earth or air, fire or water, or any of their compounds or their constituents. But if we speak of it as an invisible and characterless sort of thing, one that receives all things and shares in a most perplexing way in what is intelligible, a thing extremely difficult to comprehend, we shall not be misled. And in so far as it is possible to arrive at its nature on the basis of what we've said so far, the most correct way to speak of it may well be this: the part of it that gets ignited appears on each occasion as fire, the dampened part as water, and parts as earth or air in so far as it receives the imitations of these.

[. . .]

The third type is space, which exists always and cannot be destroyed. It provides a fixed state for all things that come to be. It is itself apprehended by a kind of bastard reasoning that does not involve sense perception, and it is hardly even an object of conviction. We look at it as in a dream when we say that everything that exists must of necessity be somewhere, in some place and occupying some space, and that that which doesn't exist somewhere, whether on earth or in heaven, doesn't exist at all.

[. . .]

Now as the wetnurse of becoming turns watery and fiery and receives the character of earth and air, and as it acquires all the properties that come with these characters, it takes on a variety of visible aspects, but because it is filled with powers that are neither similar nor evenly balanced, no part of it is in balance. It sways irregularly in every direction as it is shaken by those things, and being set in motion it in turn shakes them. And as they are moved, they drift continually, some in one direction and others in others, separating from one another. They are winnowed out, as it were, like grain that is sifted by winnowing sieves or other such implements. They are carried off and settle down, the dense and heavy ones in one direction, and the rare and light ones to another place.

That is how at that time the four kinds were being shaken by the receiver, which was itself agitating like a shaking machine, separating the kinds most unlike each other furthest apart and pushing those most like each other closest together into the same region. This, of course, explains how these different kinds came to occupy different regions of space, even before the universe was set in order and constituted from them at its coming to be.

[. . .]

Everyone knows, I'm sure, that fire, earth, water and air are bodies. Now everything that has bodily form also has depth. Depth, moreover, is of necessity comprehended within surface, and any surface bounded by straight lines is composed of triangles. Every triangle, moreover, derives from two triangles, each of which has one right angle and two acute angles. Of these two triangles, one [the isosceles right-angled triangle] has at each of the other two vertices an equal part of a right angle, determined by its division by equal sides; while the other [the scalene right-angled triangle] has unequal parts of a right angle at its other two vertices, determined by the division of the right angle by unequal sides. This, then, we presume to be the originating principle of fire and of the other bodies, as we pursue our likely account in terms of Necessity. Principles yet more ultimate than these are known only to the god, and to any man he may hold dear.

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1.5

The Structure and Motion of the Heavenly Spheres

Aristotle

Aristotle (384–322 BC), the most famous pupil of Plato and the personal tutor of Alexander the Great, was perhaps the most influential philosopher of all time. In this selection from the twelfth book of his *Metaphysics*, Aristotle makes the connection between his conception of substances and the details of his cosmology. The sphere of the stars and the spheres of individual planets must each be moved by something else, a substance unmovable in itself and eternal. The actual motions of the planets, however, are very troublesome; each planet exhibits multiple motions and requires a separate cause for each motion. To take the sun and moon into account as well requires a total of 55 spheres. Aristotle's discussion is noteworthy for the caution he displays, repeatedly referring to his conjectures as "reasonable" rather than as demonstrative and leaving the issue of whether the number of the spheres is a matter of necessity to "more powerful minds."

We must not ignore the question whether we have to suppose one such substance or more than one, and if the latter, how many; we must also mention, regarding the opinions expressed by others, that they have said nothing that can even be clearly stated about the number of the substances. For the theory of Ideas has no special discussion of the subject; for those who believe in Ideas say the Ideas are numbers, and they speak of numbers now as unlimited, now as limited by the number 10; but as for the reason why there should be just so many numbers, nothing is said with any demonstrative exactness.

We however must discuss the subject, starting from the presuppositions and distinctions we have mentioned. The first principle or primary being is not movable either in itself or accidentally, but produces the primary eternal and single movement. And since that which is moved must be moved by something, and the first

From *The Complete Works of Aristotle*, ed. Jonathan Barnes, Vol. 1 (Princeton, NJ: Princeton University Press, 1984), pp. 329–42.

mover must be in itself unmovable, and eternal movement must be produced by something eternal and a single movement by a single thing, and since we see that besides the simple spatial movement of the universe, which we say the first and unmovable substance produces, there are other spatial movements – those of the planets – which are eternal (for the body which moves in a circle is eternal and unresting; we have proved these points in the *Physics*), each of *these* movements also must be caused by a substance unmovable in itself and eternal. For the nature of the stars is eternal, being a kind of substance, and the mover is eternal and prior to the moved, and that which is prior to a substance must be a substance. Evidently, then, there must be substances which are of the same number as the movements of the stars, and in their nature eternal, and in themselves unmovable, and without magnitude, for the reason before mentioned.

That the movers are substances, then, and that one of these is first and another second according to the same order as the movements of the stars, is evident. But in the number of movements we reach a problem which must be treated from the standpoint of that one of the mathematical sciences which is most akin to philosophy – viz. of astronomy; for this science speculates about substance which is perceptible but eternal, but the other mathematical sciences, i.e. arithmetic and geometry, treat of no substance. That the movements are more numerous than the bodies that are moved, is evident to those who have given even moderate attention to the matter; for each of the planets has more than one movement. But as to the actual number of these movements, we now – to give some notion of the subject – quote what some of the mathematicians say, that our thought may have some definite number to grasp; but, for the rest, we must partly investigate for ourselves, partly learn from other investigators, and if those who study this subject form an opinion contrary to what we have now stated, we must esteem both parties indeed, but follow the more accurate.

Eudoxus supposed that the motion of the sun or of the moon involves, in either case, three spheres, of which the first is the sphere of the fixed stars, and the second moves in the circle which runs along the middle of the zodiac, and the third in the circle which is inclined across the breadth of the zodiac; but the circle in which the moon moves is inclined at a greater angle than that in which the sun moves. And the motion of the planets involves, in each case, four spheres, and of these also the first and second are the same as the first two mentioned above (for the sphere of the fixed stars is that which moves all the other spheres, and that which is placed beneath this and has its movement in the circle which bisects the zodiac is common to all), but the *poles* of the third sphere of each planet are in the circle which bisects the zodiac, and the motion of the fourth sphere is in the circle which is inclined at an angle to the equator of the third sphere; and the poles of the third spheres are different for the other planets, but those of Venus and Mercury are the same.

Callippus made the position of the spheres the same as Eudoxus did, but while he assigned the same number as Eudoxus did to Jupiter and to Saturn, he thought two more spheres should be added to the sun and two to the moon, if we were to explain the phenomena, and one more to each of the other planets.

But it is necessary, if all the spheres combined are to explain the phenomena, that for each of the planets there should be other spheres (one fewer than those hitherto assigned) which counteract those already mentioned and bring back to the same position the first sphere of the star which in each case is situated below the star in question; for only thus can all the forces at work produce the motion of the planets. Since, then, the spheres by which the planets themselves are moved are eight and twenty-five, and of these only those by which the lowest-situated planet is moved need not be counteracted, the spheres which counteract those of the first two planets will be six in number, and the spheres which counteract those of the next four planets will be sixteen, and the number of all the spheres – those which move the planets and those which counteract these – will be fifty-five. And if one were not to add to the moon and to the sun the movements we mentioned, all the spheres will be forty-nine in number.

Let this then be taken as the number of the spheres, so that the unmovable substances and principles may reasonably be taken as just so many; the assertion of *necessity* must be left to more powerful thinkers.

If there can be no spatial movement which does not conduce to the moving of a star, and if further every being and every substance which is immune from change and in virtue of itself has attained to the best must be considered an end, there can be no other being apart from these we have named, but this must be the number of the substances. For if there are others, they will cause change as being an end of movement; but there *cannot* be other movements besides those mentioned. And it is reasonable to infer this from a consideration of the bodies that are moved; for if everything that moves is for the sake of that which is moved, and every movement belongs to something that is moved, no movement can be for the sake of itself or of another movement, but all movements must be for the sake of the stars. For if a movement is to be for the sake of a movement, this latter also will have to be for the sake of something else; so that since there cannot be an infinite regress, the end of every movement will be one of the divine bodies which move through the heaven.

Evidently there is but one heaven. For if there are many heavens as there are many men, the moving principles, of which each heaven will have one, will be one in form but in number many. But all things that are many in number have matter. (For one and the same formula applies to *many* things, e.g. the formula of man; but Socrates is *one*.) But the primary essence has not matter; for it is fulfillment. So the unmovable first mover is one both in formula and in number; therefore also that which is moved always and continuously is one alone; therefore there is one heaven alone.

Our forefathers in the most remote ages have handed down to us their posterity a tradition, in the form of a myth, that these substances are gods and that the divine encloses the whole of nature. The rest of the tradition has been added later in mythical form with a view to the persuasion of the multitude and to its legal and utilitarian expediency; they say these gods are in the form of men or like some of the other animals, and they say other things consequent on and similar to these which we have mentioned. But if we were to separate the first point from these additions and take it alone – that they thought the first substances to be gods – we must regard this as an inspired utterance, and reflect that, while probably each art and science has often been developed as far as possible and has again perished, these opinions have been preserved like relics until the present. Only thus far, then, is the opinion of our ancestors and our earliest predecessors clear to us.

1.6

Change, Natures, and Causes

Aristotle

It is easy for us to take for granted the organization of the various branches of science and the principal concepts that are used to frame scientific inquiry. But when science was first being born, none of these things was obvious. In this selection from the second book of his *Physics*, Aristotle methodically addresses a number of fundamental questions: How many elements, or simple bodies, are there? Which things have innate impulses to change, and which are changed only by external causes? What senses can be given to the notion of the natures of things, and which sense is primary for science? In how many distinct senses do we use the word "cause"? What are the relations among necessity, spontaneity, and chance?

1 Of things that exist, some exist by nature, some from other causes. By nature the animals and their parts exist, and the plants and the simple bodies (earth, fire, air, water) – for we say that these and the like exist by nature.

All the things mentioned plainly differ from things which are *not* constituted by nature. For each of them has within itself a principle of motion and of stationariness (in respect of place, or of growth and decrease, or by way of alteration). On the other hand, a bed and a coat and anything else of that sort, *qua* receiving these designations – i.e. in so far as they are products of art – have no innate impulse to change. But in so far as they happen to be composed of stone or of earth or of a mixture of the two, they *do* have such an impulse, and just to that extent – which seems to indicate that nature is a principle or cause of being moved and of being at rest in that to which it belongs primarily, in virtue of itself and not accidentally.

I say 'not accidentally', because (for instance) a man who is a doctor might himself be a cause of health to himself. Nevertheless it is not in so far as he is a patient that he possesses the art of medicine: it merely has happened that the same man is doctor and patient – and that is why these attributes are not always found together. So

From *The Complete Works of Aristotle*, ed. Jonathan Barnes, Vol. 1 (Princeton, NJ: Princeton University Press, 1984), pp. 329–42.

it is with all other artificial products. None of them has in itself the principle of its own production. But while in some cases (for instance houses and the other products of manual labour) that principle is in something else external to the thing, in others – those which may cause a change in themselves accidentally – it lies in the things themselves (but not in virtue of what they are).

Nature then is what has been stated. Things have a nature which have a principle of this kind. Each of them is a substance; for it is a subject, and nature is always in a subject.

The term 'according to nature' is applied to all these things and also to the attributes which belong to them in virtue of what they are, for instance the property of fire to be carried upwards – which is not a nature nor has a nature but is by nature or according to nature.

What nature is, then, and the meaning of the terms 'by nature' and 'according to nature', has been stated. *That* nature exists, it would be absurd to try to prove; for it is obvious that there are many things of this kind, and to prove what is obvious by what is not is the mark of a man who is unable to distinguish what is self-evident from what is not. (This state of mind is clearly possible. A man blind from birth might reason about colours.) Presumably therefore such persons must be talking about words without any thought to correspond.

Some identify the nature or substance of a natural object with that immediate constituent of it which taken by itself is without arrangement, e.g. the wood is the nature of the bed, and the bronze the nature of the statue.

As an indication of this Antiphon points out that if you planted a bed and the rotting wood acquired the power of sending up a shoot, it would not be a bed that would come up, but *wood* which shows that the arrangement in accordance with the rules of the art is merely an accidental attribute, whereas the substance is the other, which, further, persists continuously through the process.

But if the material of each of these objects has itself the same relation to something else, say bronze (or gold) to water, bones (or wood) to earth and so on, *that* (they say) would be their nature and substance. Consequently some assert earth, others fire or air or water or some or all of these, to be the nature of the things that are. For whatever any one of them supposed to have this character – whether one thing or more than one thing – this or these he declared to be the whole of substance, all else being its affections, states, or dispositions. Every such thing they held to be eternal (for it could not pass into anything else), but other things to come into being and cease to be times without number.

This then is one account of nature, namely that it is the primary underlying matter of things which have in themselves a principle of motion or change.

Another account is that nature is the shape or form which is specified in the definition of the thing.

For the word 'nature' is applied to what is according to nature and the natural in the same way as 'art' is applied to what is artistic or a work of art. We should not say in the latter case that there is anything artistic about a thing, if it is a bed only potentially, not yet having the form of a bed; nor should we call it a work of art. The same is true of natural compounds. What is potentially flesh or bone has not yet its own nature, and does not exist by nature, until it receives the form specified in the definition, which we name in defining what flesh or bone is. Thus on the second account of nature, it would be the shape or form (not separable except in statement) of things which have in themselves a principle of motion. (The combination of the two, e.g. man, is not nature but by nature.)

The form indeed is nature rather than the matter; for a thing is more properly said to be what it is when it exists in actuality than when it exists potentially. Again man is born from man but not bed from bed. That is why people say that the shape is not the nature of a bed, but the wood is – if the bed sprouted, not a bed but wood would come up. But even if the shape *is* art, then on the same principle the shape of man is his nature. For man is born from man.

Again, nature in the sense of a coming-to-be proceeds towards nature. For it is not like doctoring, which leads not to the art of doctoring but to health. Doctoring must start from the art, not lead to it. But it is not in this way that nature is related to nature. What grows *qua* growing grows from something into something. Into what then does it grow? Not into that from which it arose but into that to which it tends. The shape then is nature.

Shape and nature are used in two ways. For the privation too is in a way form. But whether in unqualified coming to be there is privation, i.e. a contrary, we must consider later.

2 We have distinguished, then, the different ways in which the term 'nature' is used.

The next point to consider is how the mathematician differs from the student of nature; for natural bodies contain surfaces and volumes, lines and points, and these are the subject-matter of mathematics.

Further, is astronomy different from natural science or a department of it? It seems absurd that the student of nature should be supposed to know the nature of sun or moon, but not to know any of their essential attributes, particularly as the writers on nature obviously do discuss their shape and whether the earth and the world are spherical or not.

Now the mathematician, though he too treats of these things, nevertheless does not treat of them as the limits of a natural body; nor does he consider the attributes indicated as the attributes of such bodies. That is why he separates them; for in thought they are separable from motion, and it makes no difference, nor does any falsity result, if they are separated. The holders of the theory of Forms do the same, though they are not aware of it; for they separate the objects of natural science, which are less separable than those of mathematics. This becomes plain if one tries to state in each of the two cases the definitions of the things and of their attributes. Odd and even, straight and curved, and likewise number, line, and figure, do not involve motion; not so flesh and bone and man – *these* are defined like snub nose, not like curved.

Similar evidence is supplied by the more natural of the branches of mathematics, such as optics, harmonics, and astronomy. These are in a way the converse of geometry. While geometry investigates natural lines but not *qua* natural, optics investigates mathematical lines, but *qua* natural, not *qua* mathematical.

Since two sorts of thing are called nature, the form and the matter, we must investigate its objects as we would the essence of snubness, that is neither independently of matter nor in terms of matter only. Here too indeed one might raise a difficulty. Since there are two natures, with which is the student of nature concerned? Or should he investigate the combination of the two? But if the combination of the two, then also each severally. Does it belong then to the same or to different sciences to know each severally?

If we look at the ancients, natural science would seem to be concerned with the *matter*. (It was only very slightly that Empedocles and Democritus touched on form and essence.)

But if on the other hand art imitates nature, and it is the part of the same discipline to know the form and the matter up to a point (e.g. the doctor has a knowledge of health and also of bile and phlegm, in which health is realized and the builder both of the form of the house and of the matter, namely that it is bricks and beams, and so forth): if this is so, it would be the part of natural science also to know nature in both its senses.

Again, that for the sake of which, or the end, belongs to the same department of knowledge as the means. But the nature is the end or that for the sake of which. For if a thing undergoes a continuous change toward some end, that last stage is actually that for the sake of which. (That is why the poet was carried away into making an absurd statement when he said 'he has the end for the sake of which he was born'. For not every stage that is last claims to be an end, but only that which is best.)

For the arts make their material (some simply make it, others make it serviceable), and we use everything as if it was there for our sake. (We also are in a sense an end. 'That for the sake of which' may be taken in two ways, as we said in our work *On Philosophy*.) The arts, therefore, which govern the matter and have knowledge are two, namely the art which uses the product and the art which directs the production of it. That is why the using art also is in a sense directive; but it differs in that it knows the form, whereas the art which is directive as being concerned with production knows the matter. For the helmsman knows and prescribes what sort of form a helm should have, the other from what wood it should be made and by means of what operations. In the products of art, however, we make the material with a view to the function, whereas in the products of nature the matter is there all along.

Again, matter is a relative thing – for different forms there is different matter.

How far then must the student of nature know the form or essence? Up to a point, perhaps, as the doctor must know sinew or the smith bronze (i.e. until he understands the purpose of each); and the student of nature is concerned only with things whose forms are separable indeed, but do not exist apart from matter. Man is begotten by man and by the sun as well. The mode of existence and essence of the separable it is the business of first philosophy to define.

3 Now that we have established these distinctions, we must proceed to consider causes, their character and number. Knowledge is the object of our inquiry, and men do not think they know a thing till they have grasped the 'why' of it (which is to grasp its primary cause). So clearly we too must do this as regards both coming to be and passing away and every kind of natural change, in order that, knowing their principles, we may try to refer to these principles each of our problems.

In one way, then, that out of which a thing comes to be and which persists, is called a cause, e.g. the bronze of the statue, the silver of the bowl, and the genera of which the bronze and the silver are species.

In another way, the form or the archetype, i.e. the definition of the essence, and its genera, are called causes (e.g. of the octave the relation of 2 : 1, and generally number), and the parts in the definition.

Again, the primary source of the change or rest; e.g. the man who deliberated is a cause, the father is cause of the child, and generally what makes of what is made and what changes of what is changed.

Again, in the sense of end or that for the sake of which a thing is done, e.g. health is the cause of walking about. ('Why is he walking about?' We say: 'To be healthy', and, having said that, we think we have assigned the cause.) The same is true also of all the intermediate steps which are brought about through the action of something else as means towards the end, e.g. reduction of flesh, purging, drugs, or surgical instruments are means towards health. All these things are for the sake of the end, though they differ from one another in that some are activities, others instruments.

This then perhaps exhausts the number of ways in which the term 'cause' is used.

As things are called causes in many ways, it follows that there are several causes of the same thing (not merely accidentally), e.g. both the art of the sculptor and the bronze are causes of the statue. These are causes of the statue qua statue, not in virtue of anything else that it may be – only not in the same way, the one being the material cause, the other the cause whence the motion comes. Some things cause each other reciprocally, e.g. hard work causes fitness and vice versa, but again not in the same way, but the one as end, the other as the principle of motion. Further the same thing is the cause of contrary results. For that which by its presence brings about one result is sometimes blamed for bringing about the contrary by its absence. Thus we ascribe the wreck of a ship to the absence of the pilot whose presence was the cause of its safety.

All the causes now mentioned fall into four familiar divisions. The letters are the causes of syllables, the material of artificial products, fire and the like of bodies, the parts of the whole, and the premisses of the conclusion, in the sense or 'that from which'. Of these pairs the one set are causes in the sense of what underlies, e.g. the parts, the other set in the sense of essence – the whole and the combination and the form. But the seed and the doctor and the deliberator, and generally the maker, are all sources whence the change or stationariness originates, which the others are causes in the sense of the end or the good of the rest; for that for the sake of which tends to be what is best and the end of the things that lead up to it. (Whether we call it good or apparently good makes no difference.)

Such then is the number and nature of the kinds of cause.

Now the modes of causation are many, though when brought under heads they too can be reduced in number. For things are called causes in many ways and even within the same kind one may be prior to another: e.g. the doctor and the expert are causes of health, the relation 2 : 1 and number of the octave, and always what is inclusive to what is particular. Another mode of causation is the accidental and its genera, e.g. in one way Polyclitus, in another a sculptor is the cause of a statue, because being Polyclitus and a sculptor are accidentally conjoined. Also the classes in which the accidental attribute is included; thus a man could be said to be the cause of a statue or, generally, a living creature. An accidental attribute too may be more or less remote, e.g. suppose that a pale man or a musical man were said to be the cause of the statue.

All causes, both proper and accidental, may be spoken of either as potential or as actual; e.g. the cause of a house being built is either a house-builder or a house-builder building.

Similar distinctions can be made in the things of which the causes are causes, e.g. of this statue or of a statue or of an image generally, of this bronze or of bronze or of material generally. So too with the accidental attributes. Again we may use a complex expression for either and say, e.g., neither 'Polyclitus' nor a 'sculptor' but 'Polyclitus, the sculptor'.

All these various uses, however, come to six in number, under each of which again the usage is twofold. It is either what is particular or a genus, or an accidental attribute or a genus of that, and these either as a complex or each by itself; and all either as actual or as potential. The difference is this much, that causes which are actually at work and particular exist and cease to exist simultaneously with their effect, e.g. this healing person with this being-healed person and that housebuilding man with that being-built house; but this is not always true of potential causes – the house and the housebuilder do not pass away simultaneously.

In investigating the cause of each thing it is always necessary to seek what is most precise (as also in other things): thus a man builds because he is a builder, and a builder builds in virtue of his art of building. This last cause then is prior; and so generally.

Further, generic effects should be assigned to generic causes, particular effects to particular causes, e.g. statue to sculptor, this statue to this sculptor; and powers are relative to possible effects, actually operating causes to things which are actually being effected.

This must suffice for our account of the number of causes and the modes of causation.

4 But chance and spontaneity are also reckoned among causes: many things are said both to be and to come to be as a result of chance and spontaneity. We must inquire therefore in what manner chance and spontaneity are present among the causes enumerated, and whether they are the same or different, and generally what chance and spontaneity are.

Some people even question whether there are such things or not. They say that nothing happens by chance, but that everything which we ascribe to chance or spontaneity has some definite cause, e.g. coming by chance into the market and finding there a man whom one wanted but did not expect to meet is due to one's wish to go and buy in the market. Similarly, in other so-called cases of chance it is always possible, they maintain, to find something which is the cause; but not chance, for if chance were real, it would seem strange indeed, and the question might be raised, why on earth none of the wise men of old in speaking of the causes of generation and decay took account of chance; whence it would seem that they too did not believe that anything is by chance. But there is a further circumstance that is surprising. Many things both come to be and are by chance and spontaneity, and although all know that each of them can be ascribed to some cause (as the old argument said which denied chance), nevertheless they all speak of some of these things as happening by chance and others not. For this reason they ought to have at least referred to the matter in some way or other.

Certainly the early physicists found no place for chance among the causes which they recognized – love, strife, mind, fire, or the like. This is strange, whether they supposed that there is no such thing as chance or whether they thought there is but omitted to mention it – and that too when they sometimes used it, as Empedocles does when he says that the air is not always separated into the highest region, but as it may chance. At any rate he says in his cosmogony that 'it happened to run that way at that time, but it often ran otherwise'. He tells us also that most of the parts of animals came to be by chance.

There are some who actually ascribe this heavenly sphere and all the worlds to spontaneity. They say that the vortex arose spontaneously, i.e. the motion that separated and arranged the universe in its present order. This statement might well cause surprise. For they are asserting that chance is not responsible for the existence or generation of animals and plants, nature or mind or something of the kind being the cause of them (for it is not any chance thing that comes from a given seed but an olive from one kind and a man from another); and yet at the same time they assert that the heavenly sphere and the divinest of visible things arose spontaneously, having no such cause as is assigned to animals and plants. Yet if this is so, it is a fact which deserves to be dwelt upon, and something might well have been said about it. For besides the other absurdities of the statement, it is the more absurd that people should make it when they see nothing coming to be spontaneously in the heavens, but much happening by chance among the things which as they say are not due to chance; whereas we should have expected exactly the opposite.

Others there are who believe that chance is a cause, but that it is inscrutable to human intelligence, as being a divine thing and full of mystery.

Thus we must inquire what chance and spontaneity are, whether they are the same or different, and how they fit into our division of causes.

5 First then we observe that some things always come to pass in the same way, and others for the most part. It is clearly of neither of these that chance, or the result of chance, is said to be the cause – neither of that which is by necessity and always, nor of that which is for the most part. But as there is a third class of events besides these two – events which all say are by chance – it is plain that there is such a thing as chance and spontaneity; for we know that things of this kind are due to chance and that things due to chance are of this kind.

Of things that come to be, some come to be for the sake of something, others not. Again, some of the former class are in accordance with intention, others not, but both are in the class of things which are for the sake of something. Hence it is clear that even among the things which are outside what is necessary and what is for the most part, there are some in connexion with which the phrase 'for the sake of something' is applicable. (Things that are for the sake of something include whatever may be done as a result of thought or of nature.) Things of this kind, then, when they come to pass accidentally are said to be by chance. For just as a thing is something either in virtue of itself or accidentally, so may it be a cause. For instance, the housebuilding faculty is in virtue of itself a cause of a house, whereas the pale or the musical is an accidental cause. That which is *per se* cause is determinate, but the accidental cause is indeterminable; for the possible attributes of an individual are innumerable. As we said, then, when a thing of this kind comes to pass among events which are for the sake of something, it is said to be spontaneous or by chance. (The distinction between the two must be made later – for the present it is sufficient if it is plain that both are in the sphere of things done for the sake of something.)

Example: A man is engaged in collecting subscriptions for a feast. He would have gone to such and such a place for the purpose of getting the money, if he had known. He actually went there for another purpose, and it was only accidentally that he got his money by going there; and this was not due to the fact that he went there as a rule or necessarily, nor is the end effected (getting the money) a cause present in himself – it belongs to the class of things that are objects of choice and the result of thought. It is when these conditions are satisfied that the man is said to have gone by chance. If he had chosen and gone for the sake of this – if he always or normally went there when he was collecting payments – he would not be said to have gone by chance.

It is clear then that chance is an accidental cause in the sphere of those actions for the sake of something which involve choice. Thought, then, and chance are in the same sphere, for choice implies thought.

It is necessary, no doubt, that the causes of what comes to pass by chance be indefinite; and that is why chance is supposed to belong to the class of the indefinite and to be inscrutable to man, and why it might be thought that, in a way, nothing occurs by chance. For all these statements are correct, as might be expected. Things *do*, in a way, occur by chance, for they occur accidentally and chance is an accidental cause. But it is not the cause without qualification of anything; for instance, a housebuilder is the cause of a house; accidentally, a fluteplayer may be so.

And the causes of the man's coming and getting the money (when he did not come for the sake of that) are innumerable. He may have wished to see somebody or been following somebody or avoiding somebody, or may have gone to see a spectacle. Thus to say that chance is unaccountable is correct. For an account is of what holds always or for the most part, whereas chance belongs to a third type of event. Hence, since causes of this kind are indefinite, chance too is indefinite. (Yet in some cases one might raise the question whether *any* chance fact might be the cause of the chance occurrence, e.g. of health the fresh air or the sun's heat may be the cause, but having had one's hair cut *cannot*; for some accidental causes are more relevant to the effect than others.)

Chance is called good when the result is good, evil when it is evil. The terms 'good fortune' and 'ill fortune' are used when either result is of considerable magnitude. Thus one who comes within an ace of some great evil or great good is said to be fortunate or unfortunate. The mind affirms the presence of the attribute, ignoring the hair's breadth of difference. Further, it is with reason that good fortune is regarded as unstable; for chance is unstable, as none of the things which result from it can hold always or for the most part.

Both are then, as I have said, accidental causes – both chance and spontaneity – in the sphere of things which are capable of coming to pass not simply, nor for the most part and with reference to such of these as might come to pass for the sake of something.

6 They differ in that spontaneity is the wider. Every result of chance is from what is spontaneous, but not everything that is from what is spontaneous is from chance.

Chance and what results from chance are appropriate to agents that are capable of good fortune and of action generally. Therefore necessarily chance is in the sphere of actions. This is indicated by the fact that good fortune is thought to be the same, or nearly the same, as happiness, and happiness to be a kind of action, since it is well-doing. Hence what is not capable of action cannot do anything by chance. Thus an inanimate thing or a beast or a child cannot do anything by chance, because it is incapable of choice; nor can good fortune or ill fortune be ascribed to them, except metaphorically, as Protarchus, for example, said that the stones of which altars are made are fortunate because they are held in honour, while their fellows are trodden under foot. Even these things, however, can in a way be affected by chance, when one who is dealing with them does something to them by chance, but not otherwise.

The spontaneous on the other hand is found both in the beasts and in many inanimate objects. We say, for example, that the horse came spontaneously, because, though his coming saved him, he did not come for the sake of safety. Again, the tripod fell spontaneously, because, though it stood on its feet so as to serve for a seat, it did not fall so as to serve for a seat.

Hence it is clear that events which belong to the general class of things that may come to pass for the sake of something, when they come to pass not for the sake of what actually results, and have an external cause, may be described by the phrase 'from spontaneity'. These spontaneous events are said to be from chance if they have the further characteristics of being the objects of choice and happening to agents capable of choice. This is indicated by the phrase 'in vain', which is used when one thing which is for the sake of another, does not result in it. For instance, taking a walk is for the sake of evacuation of the bowels; if this does not follow after walking, we say that we have walked in vain and that the walking was vain. This implies that what is naturally for the sake of an end is in vain, when it does not effect the end for the sake of which it was the natural means – for it would be absurd for a man to say that he had bathed in vain because the sun was not eclipsed, since the one was not done for the sake of the other. Thus the spontaneous is even according to its derivation the case in which the thing itself happens in vain. The stone that struck the man did not fall for the sake of striking him; therefore it fell spontaneously, because it might have fallen by the action of an agent and for the sake of striking. The difference between spontaneity and what results by chance is greatest in things that come to be by nature; for when anything comes to be contrary to nature, we do not say that it came to be by chance, but by spontaneity. Yet strictly this too is different from the spontaneous proper; for the cause of the latter is external, that of the former internal.

We have now explained what chance is and what spontaneity is, and in what they differ from each other. Both belong to the mode of causation 'source of change', for either some natural or some intelligent agent is always the cause; but in this sort of causation the number of possible causes is infinite.

Spontaneity and chance are causes of effects which, though they might result from intelligence or nature, have in fact been caused by something accidentally. Now since nothing which is accidental is prior to what is *per se*, it is clear that no accidental cause can be prior to a cause *per se*. Spontaneity and chance, therefore, are posterior to intelligence and nature. Hence, however true it may be that the heavens are due to spontaneity, it will still be true that intelligence and nature will be prior causes of this universe and of many things in it besides.

7 It is clear then that there are causes, and that the number of them is what we have stated. The number is the same as that of the things comprehended under the question 'why'. The 'why' is referred ultimately either, in things which do not involve motion, e.g. in mathematics, to the 'what' (to the definition of straight line or commensurable or the like); or to what initiated a motion, e.g. 'why did they go to war? – because there had been a raid'; or we are inquiring 'for the sake of what?' – 'that they may rule'; or in the case of things that come into being, we are looking for the matter. The causes, therefore, are these and so many in number.

Now, the causes being four, it is the business of the student of nature to know about them all, and if he refers his problems back to all of them, he will assign the 'why' in the way proper to his science – the matter, the form, the mover, that for the sake of which. The last three often coincide; for the what and that for the sake of which are one, while the primary source of motion is the same in species as these. For man generates man – and so too, in general, with all things which cause movement by being themselves moved; and such as are not of this kind are no longer inside the province of natural science, for they cause motion not by possessing motion or a source of motion in themselves, but being themselves incapable of motion. Hence there are three branches of study, one of things which are incapable of motion, the second of things in motion, but indestructible, the third of destructible things.

The question 'why', then, is answered by reference to the matter, to the form, and to the primary moving cause. For in respect of coming to be it is mostly in this last way that causes are investigated – 'what comes to be after what? what was the primary agent or patient?' and so at each step of the series.

Now the principles which cause motion in a natural way are two, of which one is not natural, as it has no principle of motion in itself. Of this kind is whatever causes movement, not being itself moved, such as that which is completely unchangeable, the primary reality, and the essence of a thing, i.e. the form; for this is the end or that for the sake of which. Hence since nature is for the sake of something, we must know this cause also. We must explain the 'why' in all the senses of the term, namely, that from this that will necessarily result ('from this' either without qualification or for the most part); that this must be so if that is to be so (as the conclusion presupposes the premisses); that this was the essence of the thing; and because it is better thus (not without qualification, but with reference to the substance in each case).

8 We must explain then first why nature belongs to the class of causes which act for the sake of something; and then about the necessary and its place in nature, for all writers ascribe things to this cause, arguing that since the hot and the cold and the like are of such and such a kind, therefore certain things *necessarily are* and come to be – and if they mention any other cause (one friendship and strife, another mind), it is only to touch on it, and then good-bye to it.

A difficulty presents itself: why should not nature work, not for the sake of something, nor because it is better so, but just as the sky rains, not in order to make the corn grow, but of necessity? (What is drawn up must cool, and what has been cooled must become water and descend, the result of this being that the corn grows.) Similarly if a man's crop is spoiled on the threshing-floor, the rain did not fall for the sake of this – in order that the crop might be spoiled – but that result just followed. Why then should it not be the same with the parts in nature, e.g. that our teeth should come up of necessity – the front teeth sharp, fitted for tearing, the molars broad and useful for grinding down the food – since they did not arise for this end, but it was merely a coincident result; and so with all other parts in which we suppose that there is purpose? Wherever then all the parts came about just what they would have been if they had come to be for an end, such things survived, being organized spontaneously in a fitting way; whereas those which grew otherwise perished and continue to perish, as Empedocles says his 'man-faced oxprogeny' did.

Such are the arguments (and others of the kind) which may cause difficulty on this point. Yet it is impossible that this should be the true view. For teeth and all other natural things either invariably or for the most part come about in a given way; but of not one of the results of chance or spontaneity is this true. We do not ascribe to chance or mere coincidence the frequency of rain in winter, but frequent rain in summer we do; nor heat in summer but only if we have it in winter. If then, it is agreed that things are either the result of coincidence or for the sake of something, and these cannot be the result of coincidence or spontaneity, it follows that they must be for the sake of something; and that such things are all due to nature even the champions of the theory which is before us would agree. Therefore action for an end is present in things which come to be and are by nature.

Further, where there is an end, all the preceding steps are for the sake of that. Now surely as in action, so in nature; and as in nature, so it is in each action, if nothing interferes. Now action is for the sake of an end; therefore the nature of things also is so. Thus if a house, e.g., had been a thing made by nature, it would have been made in the same way as it is now by art; and if things made by nature were made not only by nature but also by art, they would come to be in the same way as by nature. The one, then, is for the sake of the other; and generally art in some cases completes what nature cannot bring to a finish, and in others imitates nature. If, therefore, artificial products are for the sake of an end, so clearly also are natural products. The relation of the later to the earlier items is the same in both.

This is most obvious in the animals other than man: they make things neither by art nor after inquiry or deliberation. That is why people wonder whether it is by intelligence or by some other faculty that these creatures work, – spiders, ants, and the like. By gradual advance in this direction we come to see clearly that in plants too that is produced which is conducive to the end – leaves, e.g. grow to provide shade for the fruit. If then it is both by nature and for an end that the swallow makes its nest and the spider its web, and plants grow leaves for the sake of the fruit and send their roots down (not up) for the sake of nourishment, it is plain that this kind of cause is operative in things which come to be and are by nature. And since nature is twofold, the matter and the form, of which the latter is the end, and since all the rest is for the sake of the end, the form must be the cause in the sense of that for the sake of which.

Now mistakes occur even in the operations of art: the literate man makes a mistake in writing and the doctor pours out the wrong dose. Hence clearly mistakes are possible in the operations of nature also. If then in art there are cases in which what is rightly produced serves a purpose, and if where mistakes occur there was a purpose in what was attempted, only it was not attained, so must it be also in natural products, and monstrosities will be failures in the purposive effort. Thus in the original combinations the 'ox-progeny', if they failed to reach a determinate end must have arisen through the corruption of some principle, as happens now when the seed is defective.

Further, seed must have come into being first, and not straightway the animals: what was 'undifferentiated first' was seed.

Again, in plants too we find that for the sake of which, though the degree of organization is less. Were there then in plants also olive-headed vine-progeny, like the 'man-headed ox-progeny', or not? An absurd suggestion; yet there must have been, if there were such things among animals.

Moreover, among the seeds anything must come to be at random. But the person who asserts this entirely does away with nature and what exists by nature. For those things are natural which, by a continuous movement originated from an internal principle, arrive at some end: the same end is not reached from every principle; nor any chance end, but always the tendency in each is towards the same end, if there is no impediment.

The end and the means towards it may come about by chance. We say, for instance, that a stranger has come by chance, paid the ransom, and gone away, when he does so as if he had come for that purpose, though it was not for that that he came. This is accidental, for chance is an accidental cause, as I remarked before. But when an event takes place always or for the most part, it is not accidental or by chance. In natural products the sequence is invariable, if there is no impediment.

It is absurd to suppose that purpose is not present because we do not observe the agent deliberating. Art does not deliberate. If the ship-building art were in the wood, it would produce the same results by nature. If, therefore, purpose is present in art, it is present also in nature. The best illustration is a doctor doctoring himself: nature is like that.

It is plain then that nature is a cause, a cause that operates for a purpose.

9 As regards what is of necessity, we must ask whether the necessity is hypothetical, or simple as well. The current view places what is of necessity in the process of production, just as if one were to suppose that the wall of a house necessarily comes to be because what is heavy is naturally carried downwards and what is light to the top, so that the stones and foundations take the lowest place, with earth above because it is lighter, and wood at the top of all as being the lightest. Whereas, though the wall does not come to be *without* these, it is not *due* to these, except as its material cause: it comes to be for the sake of sheltering and guarding certain things. Similarly in all other things which involve that for the sake of which: the product cannot come to be without things which have a necessary nature, but it is not due to these (except as its material); it comes to be for an end. For instance, why is a saw such as it is? To effect so-and-so and for the sake of so-and-so. This end, however, cannot be realized unless the saw is made of iron. It is, therefore, necessary for it to be of iron, if we are to have a saw and perform the operation of sawing. What is necessary then, is necessary on a hypothesis, not as an end. Necessity is in the matter, while that for the sake of which is in the definition.

Necessity in mathematics is in a way similar to necessity in things which come to be through the operation of nature. Since a straight line is what it is, it is necessary that the angles of a triangle should equal two right angles. But not conversely; though if the angles are *not* equal to two right angles, then the straight line is not what it is either. But in things which come to be for an end, the reverse is true. If the end is to exist or does exist, that also which precedes it will exist or does exist; otherwise just as there, if the conclusion is not true, the principle will not be true, so here the end or that for the sake of which will not exist. For this too is itself a principle, but of the reasoning, not of the action. (In mathematics the principle is the principle of the reasoning only, as there is no action.) If then there is to be a house, such-and-such things must be made or be there already or exist, or generally the matter relative to the end, bricks and stones if it is a house. But the end is not due to these except as the matter, nor will it come to exist because of them. Yet if they do not exist at all, neither will the house, or the saw – the former in the absence of stones, the latter in the absence of iron – just as in the other case the principles will not be true, if the angles of the triangle are not equal to two right angles.

The necessary in nature, then, is plainly what we call by the name of matter, and the changes in it. Both causes must be stated by the student of nature, but especially the end; for that is the cause of the matter, not *vice versa*; and the end is that for the sake of which, and the principle starts from the definition or essence: as in artificial products, since a house is of such-and-such a kind, certain things must *necessarily* come to be or be there already, or since health is this, these things must necessarily come to be or be there already, so too if man is this, then these; if these, then those. Perhaps the necessary is present also in the definition. For if one defines the operation of sawing as being a certain kind of dividing, then this cannot come about unless the saw has teeth of a certain kind; and these cannot be unless it is of iron. For in the definition too there are some parts that stand as matter.

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1.7

Scientific Inference and the Knowledge of Essential Natures

Aristotle

Aristotle's work broke new ground not only in science but also in logic. The two pursuits are related. For to do science well we must reason well, and this requires that we understand the structure of good reasoning and recognize the difference between cogent reasoning and sophistry. In this selection from the first book of the *Posterior Analytics*, Aristotle discusses the nature of demonstrative inference and then argues that the proper subject matter of scientific demonstration is not just what happens accidentally but rather what belongs to things in themselves, on account of their essences, or real natures. A knowledge of those natures is, therefore, required for scientific thought.

1 All teaching and all intellectual learning come about from already existing knowledge. This is evident if we consider it in every case; for the mathematical sciences are acquired in this fashion, and so is each of the other arts. And similarly too with arguments – both deductive and inductive arguments proceed in this way; for both produce their teaching through what we are already aware of, the former getting their premisses as from men who grasp them, the latter proving the universal through the particular's being clear. (And rhetorical arguments too persuade in the same way; for they do so either through examples, which is induction, or through enthymemes, which is deduction.)

It is necessary to be already aware of things in two ways: of some things it is necessary to believe already that they are, of some one must grasp what the thing said is, and of others both – e.g. of the fact that everything is either affirmed or denied truly, one must believe that it is; of the triangle, that it signifies *this*; and of the unit both (both what it signifies and that it is). For each of these is not equally clear to us.

But you can become familiar by being familiar earlier with some things but getting knowledge

From *The Complete Works of Aristotle*, ed. Jonathan Barnes, Vol. 1 (Princeton, NJ: Princeton University Press, 1984), extracts from pp. 473, 474–6, 477–8, 480, 482–4, 486–9.

of the others at the very same time – i.e. of whatever happens to be under the universal of which you have knowledge. For that every triangle has angles equal to two right angles was already known; but that there is a triangle in the semicircle here became familiar at the same time as the induction. (For in some cases learning occurs in this way, and the last term does not become familiar through the middle – in cases dealing with what are in fact particulars and not said of any underlying subject.)

Before the induction, or before getting a deduction, you should perhaps be said to understand in a way – but in another way not. For if you did not know if it is *simpliciter*, how did you know that it has two right angles *simpliciter*? But it is clear that you understand it in *this* sense – that you understand it universally – but you do not understand it *simpliciter*. (Otherwise the puzzle in the *Meno* will result; for you will learn either nothing or what you know.)

For one should not argue in the way in which some people attempt to solve it: Do you or don't you know of every pair that it is even? And when you said Yes, they brought forward some pair of which you did not think that it was, nor therefore that it was even. For they solve it by denying that people know of every pair that it is even, but only of anything of which they know that it is a pair. – Yet they know it of that which they have the demonstration about and which they got their premisses about; and they got them not about everything of which they know that it is a triangle or that it is a number, but of every number and triangle *simpliciter*. For no proposition of such a type is assumed (that *what you know to be a number* . . . or *what you know to be rectilineal* . . .), but they are assumed as holding of every case.

But nothing, I think, prevents one from in a sense understanding and in a sense being ignorant of what one is learning; for what is absurd is not that you should know in some sense what you are learning, but that you should know it in *this* sense, i.e. in the way and sense in which you are learning it.

2 We think we understand a thing *simpliciter* (and not in the sophistic fashion accidentally) whenever we think we are aware both that the explanation because of which the object is is its explanation, and that it is not possible for this to be otherwise. It is clear, then, that to understand is something of this sort; for both those who do not understand and those who do understand – the former think they are themselves in such a state, and those who do understand actually are. Hence that of which there is understanding *simpliciter* cannot be otherwise.

Now whether there is also another type of understanding we shall say later; but we say now that we do know through demonstration. By demonstration I mean a scientific deduction; and by scientific I mean one in virtue of which, by having it, we understand something.

If, then, understanding is as we posited, it is necessary for demonstrative understanding in particular to depend on things which are true and primitive and immediate and more familiar than and prior to and explanatory of the conclusion (for in this way the principles will also be appropriate to what is being proved). For there will be deduction even without these conditions, but there will not be demonstration; for it will not produce understanding.

Now they must be true because one cannot understand what is not the case – e.g. that the diagonal is commensurate. And they must depend on what is primitive and non-demonstrable because otherwise you will not understand if you do not have a demonstration of them; for to understand that of which there is a demonstration non-accidentally is to have a demonstration. They must be both explanatory and more familiar and prior – explanatory because we only understand when we know the explanation; and prior, if they are explanatory, and we are already aware of them not only in the sense of grasping them but also of knowing that they are.

Things are prior and more familiar in two ways; for it is not the same to be prior by nature and prior in relation to us, nor to be more familiar and more familiar to us. I call prior and more familiar in relation to us what is nearer to perception, prior and more familiar *simpliciter* what is further away. What is most universal is furthest away, and the particulars are nearest; and these are opposite to each other.

Depending on things that are primitive is depending on appropriate principles; for I call the same thing primitive and a principle. A principle of a demonstration is an immediate proposition, and an immediate proposition is one to which there is no other prior. A proposition is the one part of a contradiction, one thing said of one; it is dialectical if it assumes indifferently either part, demonstrative if it determinately assumes the one that is true. [A statement is either part of a contradiction.] A contradiction is an opposition of which of itself excludes any intermediate; and the part of a contradiction saying something *of* something is an affirmation, the one saying something *from* something is a denial.

An immediate deductive principle I call a posit if one cannot prove it but it is not necessary for anyone who is to learn anything to grasp it; and one which it is necessary for anyone who is going to learn anything whatever to grasp, I call an axiom (for there are some such things); for we are accustomed to use this name especially of such things. A posit which assumes either of the parts of a contradiction – i.e., I mean, that something is or that something is not – I call a supposition; one without this, a definition. For a definition is a posit (for the arithmetician posits that a unit is what is quantitatively indivisible) but not a supposition (for what a unit is and that a unit is are not the same).

Since one should both be convinced of and know the object by having a deduction of the sort we call a demonstration, and since this is the case when *these* things on which the deduction depends are the case, it is necessary not only to be already aware of the primitives (either all or some of them) but actually to be better aware of them. For a thing always belongs better to that thing because of which it belongs – e.g. that because of which we love is better loved. Hence if we know and are convinced because of the primitives, we both know and are convinced of them better, since it is because of them that we know and are convinced of what is posterior.

It is not possible to be better convinced than one is of what one knows, of what one in fact neither knows nor is more happily disposed toward than if one in fact knew. But this will result if someone who is convinced because of a demonstration is not already aware of the primitives, for it is necessary to be better convinced of the principles (either all or some of them) than of the conclusion.

Anyone who is going to have understanding through demonstration must not only be familiar with the principles and better convinced of them than of what is being proved, but also there must be no other thing more convincing to him or more familiar among the opposites of the principles on which a deduction of the contrary error may depend – if anyone who understands *simpliciter* must be unpersuadable.

3 Now some think that because one must understand the primitives there is no understanding at all; others that there is, but that there are demonstrations of everything. Neither of these views is either true or necessary.

For the one party, supposing that one cannot understand in another way, claim that we are led back *ad infinitum* on the grounds that we would not understand what is posterior because of what is prior if there are no primitives; and they argue correctly, for it is impossible to go through infinitely many things. And if it comes to a stop and there are principles, they say that these are unknowable since there is no *demonstration* of them, which alone they say is understanding; but if one cannot know the primitives, neither can what depends on them be understood *simpliciter* or properly, but only on the supposition that they are the case.

The other party agrees about understanding; for it, they say, occurs only through demonstration. But they argue that nothing prevents there being demonstration of everything; for it is possible for the demonstration to come about in a circle and reciprocally.

But *we* say that neither is all understanding demonstrative, but in the case of the immediates it is non-demonstrable – and that this is necessary is evident; for if it is necessary to understand the things which are prior and on which the demonstration depends, and it comes to a stop at some time, it is necessary for these immediates to be non-demonstrable. So as to that we argue thus; and we also say that there is not only understanding but also some principle of understanding by which we become familiar with the definitions.

And that it is impossible to demonstrate *simpliciter* in a circle is clear, if demonstration must depend on what is prior and more familiar; for it is impossible for the same things at the same time to be prior and posterior to the same things – unless one is so in another way (i.e. one in relation to us, the other *simpliciter*), which induction makes familiar. But if so, knowing *simpliciter* will not have been properly defined, but will be twofold. Or is the other demonstration not demonstration *simpliciter* in that it comes from about what is more familiar *to us*?

There results for those who say that demonstration is circular not only what has just been described, but also that they say nothing other than that this is the case if this is the case – and it is easy to prove everything in this way. It is clear that this results if we posit three terms. (For it makes no difference to say that it bends back through many terms or through few, or through few or two.) For whenever if *A* is the case, of necessity *B* is, and if this then *C*, then if *A* is the case *C* will be the case. Thus given that if *A* is the case it is necessary that *B* is, and if this is that *A* is (for that is what being circular is) – let *A* be *C*: so to say that if *B* is the case *A* is, is to say that *C* is, and this implies that if *A* is the case *C* is. But *C* is the same as *A*. Hence it results that those who assert that demonstration is circular say nothing but that if *A* is the case *A* is the ease. And it is easy to prove everything in this way.

[. . .]

6 Now if demonstrative understanding depends on necessary principles (for what one understands cannot be otherwise), and what belongs to the objects in themselves is necessary (for in the one case it belongs in what they are; and in the other they belong in what they are to what is predicated of them, one of which opposites necessarily belongs), it is evident that demonstrative deduction will depend on things of this sort; for everything belongs either in this way or accidentally, and what is accidental is not necessary.

Thus we must either argue like this, or, positing as a principle that demonstration is necessary and that if something has been demonstrated it cannot be otherwise – the deduction, therefore, must depend on necessities. For from truths one can deduce *without* demonstrating, but from necessities one cannot deduce without demonstrating; for this is precisely the mark of demonstration.

There is evidence that demonstration depends on necessities in the fact that this is how we bring our objections against those who think they are demonstrating – saying that it is not necessary, if we think either that it is absolutely possible for it to be otherwise, or at least for the sake of argument.

From this it is clear too that those people are silly who think they get their principles correctly if the proposition is reputable and true (e.g. the sophists who assume that to understand is to have understanding). For it is not what is reputable or not that is a principle, but what is primitive in the genus about which the proof is; and not every truth is appropriate.

That the deduction must depend on necessities is evident from this too: if, when there is a demonstration, a man who has not got an account of the reason why does not have understanding, and if it might be that *A* belongs to *C* from necessity but that *B*, the middle term through which it was demonstrated, does not hold from necessity, then he does not know the reason why. For this is not so because of the middle term; for it is possible for that not to be the case, whereas the conclusion is necessary.

Again, if someone does not know now, though he has got the account and is preserved, and the object is preserved, and he has not forgotten, then he did not know earlier either. But the middle term might perish if it is not necessary; so that though, being himself preserved and the object preserved, he will have the account, yet he does not know. Therefore, he did not know earlier either. And if it has not perished but it is possible for it to perish, the result would be capable of occurring and possible; but it is impossible to know when in such a state.

Now when the conclusion is from necessity, nothing prevents the middle term through which it was proved from being non-necessary; for one can deduce a necessity from a non-necessity, just as one can deduce a truth from non-truths. But when the middle term is from necessity, the conclusion too is from necessity, just as from truths it is always true; for let *A* be said of *B* from necessity, and this of *C* – then that *A* belongs to *C* is also necessary. But when the conclusion is not necessary, the middle term cannot be necessary either; for let *A* belong to *C* not from necessity, but to *B* and this to *C* from necessity – therefore *A* will belong to *C* from necessity too; but it was supposed not to.

Since, then, if a man understands demonstratively, it must belong from necessity, it is clear that he must have his demonstration through a middle term that is necessary too; or else he will not understand either why or that it is necessary for that to be the case, but either he will think but not know it (if he believes to be necessary what is not necessary) or he will not even think it (equally whether he knows the fact through middle terms or the reason why actually through immediates).

Of accidentals which do not belong to things in themselves in the way in which things belonging in themselves were defined, there is no demonstrative understanding. For one cannot prove the conclusion from necessity; for it is possible for what is accidental not to belong – for that is the sort of accidental I am talking about. Yet one might perhaps puzzle about what aim we should have in asking these questions about them, if it is not necessary for the conclusion to be the case; for it makes no difference if one asks chance questions and then says the conclusion. But we must ask not as though the conclusion were necessary because of what was asked, but because it is necessary for anyone who says them to say it, and to say it truly if they truly hold.

Since in each kind what belongs to something in itself and as such belongs to it from necessity, it is evident that scientific demonstrations are about what belongs to things in themselves, and depend on such things. For what is accidental is not necessary, so that you do not necessarily know why the conclusion holds – not even if it should always be the case but not in itself (e.g. deductions through signs). For you will not understand in itself something that holds in itself; nor will you understand why it holds. (To understand why is to understand through the explanation.) Therefore the middle term must belong to the third, and the first to the middle, because of itself.

7 One cannot, therefore, prove anything by crossing from another genus – e.g. something geometrical by arithmetic. For there are three things in demonstrations: one, what is being demonstrated, the conclusion (this is what belongs to some genus in itself); one, the axioms (axioms are the things on which the demonstration depends); third, the underlying genus of which the demonstration makes clear the attributes and what is accidental to it in itself.

Now the things on which the demonstration depends may be the same; but of things whose genus is different – as arithmetic and geometry, one cannot apply arithmetical demonstrations to the accidentals of magnitudes, unless magnitudes are numbers. (How this is possible in some cases will be said later.)

Arithmetical demonstrations always include the genus about which the demonstration is, and so also do the others; hence it is necessary for the genus to be the same, either *simpliciter* or in some respect, if the demonstration is going to cross.

1.8

The Cosmos and the Shape and Size of the Earth

Aristotle

One of Aristotle's great contributions was his methodical exposition and critique of the theories of his predecessors to discover what was established. In this selection from the second book of *On the Heavens*, Aristotle argues that the universe is spherical, that its movement is regular, that the stars move around a motionless earth, and that the planets have an additional motion by which they work their way slowly backward against the wheeling background of the stars. As for the earth, Aristotle argues that it stands at the center of the universe, that it is motionless, that in comparison to the height of the stars it is of no great size, and that it is spherical. This last conclusion surprises some people who have been taught that Columbus discovered the sphericity of the earth; but this was in fact a commonplace among the educated from Aristotle's day through the Renaissance.

4 The shape of the heaven is of necessity spherical; for that is the shape most appropriate to its substance and also by nature primary.

First, let us consider generally which shape is primary among planes and solids alike. Every plane figure must be either rectilinear or curvilinear. Now the rectilinear is bounded by more than one line, the curvilinear by one only. But since in any kind the one is naturally prior to the many and the simple to the complex, the circle will be the first of plane figures.

[. . .]

Now the first figure belongs to the first body, and the first body is that at the farthest circumference. It follows that the body which revolves with a circular movement must be spherical. The

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same then will be true of the body continuous with it; for that which is continuous with the spherical is spherical. The same again holds of the bodies between these and the centre. Bodies which are bounded by the spherical and in contact with it must be, as wholes, spherical; and the lower bodies are contiguous with the sphere above them. The sphere then will be spherical throughout; for every body within it is contiguous and continuous with spheres.

Again, since the whole seems – and has been assumed – to revolve in a circle, and since it has been shown that outside the farthest circumference there is neither void nor place, from these grounds also it will follow necessarily that the heaven is spherical. For if it is to be rectilinear in shape, it will follow that there is place and body and void without it. For a rectilinear figure as it revolves never continues in the same room, but where formerly was body, is now none, and where now is none, body will be in a moment because of the changing positions of the corners. Similarly, if the world had some other figure with unequal radii, if, for instance, it were lentiform, or oviform, in every case we should have to admit space and void outside the moving body, because the whole body would not always occupy the same room.

Again, if the motion of the heaven is the measure of all movements in virtue of being alone continuous and regular and eternal, and if, in each kind, the measure is the minimum, and the minimum movement is the swiftest, then the movement of the heaven must be the swiftest of all movements. Now of lines which return upon themselves the line which bounds the circle is the shortest; and that movement is the swiftest which follows the shortest line. Therefore, if the heaven moves in a circle and moves more swiftly than anything else, it must necessarily be spherical.

Corroborative evidence may be drawn from the bodies whose position is about the centre. If earth is enclosed by water, water by air, air by fire, and these similarly by the upper bodies – which while not continuous are yet contiguous with them – and if the surface of water is spherical, and that which is continuous with or embraces the spherical must itself be spherical, then on these grounds also it is clear that the heavens are spherical. But the surface of water is seen to be spherical if we take as our starting-point the fact that water naturally tends to collect in the more hollow places – and the more hollow are those nearer the centre. Draw from the centre the lines *AB*, *AC*, and let them be joined by the straight line *BC*. The line *AD*, drawn to the base of the triangle, will be shorter than either of the radii. Therefore the place in which it terminates will be more hollow. The water then will collect there until equality is established. But the line *AE* is equal to the radii. Thus water lies at the ends of the radii, and there will it rest; but the line which connects the extremities of the radii is circular: therefore the surface of the water *BEC* is spherical.

It is plain from the foregoing that the universe is spherical. It is plain, further, that it is so accurately turned that no manufactured thing nor anything else within the range of our observation can even approach it. For the matter of which these are composed does not admit of anything like the same regularity and finish as the substance of the enveloping body; since with each step away from earth the matter manifestly becomes finer in the same proportion as water is finer than earth.

5 Now there are two ways of moving along a circle, from *A* to *B* or from *A* to *C*, and we have already explained that these movements are not contrary to one another. But nothing which concerns the eternal can be a matter of chance or spontaneity, and the heaven and its circular motion are eternal. We must therefore ask why this motion takes one direction and not the other. Either this is itself a principle or there is a principle behind it. It may seem evidence of excessive folly or excessive zeal to try to provide an explanation of some things, or of everything, admitting no exception. The criticism, however, is not always just: one should first consider what reason there is for speaking, and also what kind of certainty is looked for, whether human merely or of a more cogent kind. When any one shall succeed in finding proofs of greater precision, gratitude will be due to him for the discovery, but at present we must be content with what seems to be the case. If nature always follows the best course possible, and, just as upward movement is the superior form of rectilinear movement, since the upper region is more divine than the lower, so forward movement is superior to backward, then front and back exhibits, like right and left, as we said before and as the difficulty just stated itself suggests, the distinction of prior and posterior, which provides a reason and so solves

our difficulty. Supposing that nature is ordered in the best way possible, this may stand as the reason of the fact mentioned. For it is best to move with a movement simple and unceasing, and, further, in the superior of two possible directions.

6 We have next to show that the movement of the heaven is regular and not irregular. This applies to the first heaven and the first movement; for the lower spheres exhibit a composition of several movements into one. If the movement is uneven, clearly there will be acceleration, maximum speed, and retardation, since these appear in all irregular motions. The maximum may occur either at the starting-point or at the goal or between the two; and we expect natural motion to reach its maximum at the goal, unnatural motion at the starting-point, and missiles midway between the two. But circular movement, having no beginning or limit or middle without qualification, has neither whence nor whither nor middle; for in time it is eternal, and in length it returns upon itself without a break. If then its movement has no maximum, it can have no irregularity, since irregularity is produced by retardation and acceleration. Further, since everything that is moved is moved by something, the cause of the irregularity of movement must lie either in the mover or in the moved or in both. For if the mover moved not always with the same force, or if the moved were altered and did not remain the same, or if both were to change, the result might well be an irregular movement in the moved. But none of these possibilities can occur in the case of the heavens. As to that which is moved, we have shown that it is primary and simple and ungenerated and indestructible and generally unchanging; and it is far more reasonable to ascribe those attributes to the mover. It is the primary that moves the primary, the simple the simple, the indestructible and ungenerated that which is indestructible and ungenerated. Since then that which is moved, being a body, is nevertheless unchanging, how should the mover, which is incorporeal, be changed?

For if irregularity occurs, there must be change either in the movement as a whole, from fast to slow and slow to fast, or in its parts. That there is no irregularity in the parts is obvious, since, if there were, some divergence of the stars would have taken place before now in the infinity of time, as one moved slower and another faster; but no alteration of their intervals is ever observed. Nor again is a change in the movement as a whole admissible. Retardation is always due to incapacity, and incapacity is unnatural. The incapacities of animals, age, decay, and the like, are all unnatural, due, it seems, to the fact that the whole animal complex is made up of materials which differ in respect of their proper places, and no single part occupies its own place. If therefore that which is primary contains nothing unnatural, being simple and unmixed and in its proper place and having no contrary, then it has no place for incapacity, nor, consequently, for retardation or (since acceleration involves retardation) for acceleration. Again, it is unreasonable that the mover should first show incapacity for an infinite time, and capacity afterwards for another infinity. For clearly nothing which, like incapacity, is unnatural ever continues for an infinity of time; nor does the unnatural endure as long as the natural, or any form of incapacity as long as the capacity. But if the movement is retarded it must necessarily be retarded for an infinite time. Equally impossible is perpetual acceleration or perpetual retardation. For such movement would be infinite and indefinite; but every movement, in our view, proceeds from one point to another and is definite in character. Again, suppose one assumes a minimum time in less than which the heaven could not complete its movement. For, as a given walk or a given exercise on the harp cannot take any and every time, but every performance has its definite minimum time which is unsurpassable, so, one might suppose, the movement of the heaven could not be completed in any and every time. But in that case perpetual acceleration is impossible (and, equally, perpetual retardation; for the argument holds of both and each), if we may take acceleration to proceed by identical or increasing additions of speed and for an infinite time. The remaining possibility is to say that the movement exhibits an alternation of slower and faster; but this is a mere fiction and quite unreasonable. Further, irregularity of this kind would be particularly unlikely to pass unobserved, since contrast makes observation easy.

That there is one heaven, then, only, and that it is ungenerated and eternal, and further that its movement is regular, has now been sufficiently explained.

[. . .]

8 Since changes evidently occur not only in the position of stars but also in that of the whole heaven, there are three possibilities: either both are at rest, or both are in motion, or the one is at rest and the other in motion.

That both should be at rest is impossible; for, if the earth is at rest, the hypothesis does not account for the phenomena; and we take it as granted that the earth is at rest. It remains either that both are moved, or that the one is moved and the other at rest.

On the view, first, that both are in motion, we have the absurdity that the stars and the circles move with the same speed, i.e. that the pace of every star is that of the circle in which it moves. For star and circle are seen to come back to the same place at the same moment; from which it follows that the star has traversed the circle and the circle has completed its own movement, i.e. traversed its own circumference, at one and the same moment. But it is unreasonable that the pace of each star should be exactly proportioned to the size of its circle. That the pace of each circle should be proportionate to its size is not absurd but inevitable; but that the same should be true of the movement of the stars contained in the circles is quite unreasonable. For if the star which moves on the greater circle is necessarily swifter, clearly if the stars shifted their position so as to exchange circles, the slower would become swifter and the swifter slower. But this would show that their movement was not their own, but due to the circles. If, on the other hand, the arrangement was a chance combination, the coincidence in every case of a greater circle with a swifter movement of the star contained in it is unreasonable. In one or two cases it might not inconceivably fall out so, but to imagine it in every case alike is a mere fiction. Besides, chance has no place in that which is natural, and what happens everywhere and in every case is no matter of chance.

The same absurdity is equally plain if it is supposed that the circles stand still and that it is the stars themselves which move. For it will follow that the outer stars are the swifter, and that the pace of the stars corresponds to the size of circles.

Since, then, we cannot reasonably suppose either that both are in motion or that the star alone moves, it remains that the circles should move, while the stars are at rest and move with the circles to which they are attached. Only on this supposition are we involved in no absurd consequence. For, in the first place, the quicker movement of the larger circle is reasonable when all the circles are attached to the same centre. Whenever bodies are moving with their proper motion, the larger moves quicker. It is the same here with the revolving bodies; for the arc intercepted by two radii will be larger in the larger circle, and hence it is reasonable that the revolution of the larger circle should take the same time as that of the smaller. And secondly, the fact that the heavens do not break in pieces follows not only from this but also from the proof already given of the continuity of the whole.

[. . .]

10 With their order – I mean the movement of each, as involving the priority of some and the posteriority of others, and their distances from each other – astronomy may be left to deal, since the astronomical discussion is adequate. This discussion shows that the movements of the several stars depend, as regards the varieties of speed which they exhibit, on their distances. It is established that the outermost revolution of the heavens is a simple movement and the swiftest of all, and that the movement of all other bodies is composite and relatively slow, for the reason that each is moving on its own circle with the reverse motion to that of the heavens. This at once makes it reasonable that the body which is nearest to that first simple revolution should take the longest time to complete its circle, and that which is farthest from it the shortest, the others taking a longer time the nearer they are and a shorter time the farther away they are. For it is the nearest body which is most strongly influenced, and the most remote, by reason of its distance, which is least affected, the influence on the intermediate bodies varying, as the mathematicians show, with their distance.

[. . .]

13 It remains to speak of the earth, of its position, of the question whether it is at rest or in motion, and of its shape.

As to its *position* there is some difference of opinion. Most people – all, in fact, who regard the whole heaven as finite – say it lies at the centre. But the Italian philosophers known as Pythagoreans take the contrary view. At the centre, they say, is fire, and the earth is one of the stars, creating night and day by its circular motion about the centre. They further construct another earth in opposition to ours to which they give the name counter-earth. In all this they are not seeking for theories and causes to account for the phenomena, but rather forcing the phenomena and trying to accommodate them to certain theories and opinions of their own. But there are many others who would agree that it is wrong to give the earth the central position, looking for confirmation rather to theory than to the phenomena. Their view is that the most precious place befits the most precious thing; but fire, they say, is more precious than earth, and the limit than the intermediate, and the circumference and the centre are limits. Reasoning on this basis they take the view that it is not earth that lies at the centre of the sphere, but rather fire. The Pythagoreans have a further reason. They hold that the most important part of the world, which is the centre, should be most strictly guarded, and name the fire which occupies that place the 'Guard-house of Zeus', as if the word 'centre' were quite unequivocal, and the centre of the mathematical figure were always the same with that of the thing or the natural centre. But it is better to conceive of the case of the whole heaven as analogous to that of animals, in which the centre of the animal and that of the body are different. For this reason they have no need to be so disturbed about the world, or to call in a guard for its centre: rather let them look for the centre in the other sense and tell us what it is like and where nature has set it. That centre will be something primary and precious; but to the mere position we should give the last place rather than the first. For the middle is what is defined, and what defines it is the limit, and that which contains or limits is more precious than that which is limited, seeing that the latter is the matter and the former the substance of the system.

As to the position of the earth, then, this is the view which some advance, and the views advanced concerning its *rest or motion* are similar. For here too there is no general agreement. All who deny that the earth lies at the centre think that it revolves about the centre, and not the earth only but, as we said before, the counter-earth as well. Some of them even consider it possible that there are several bodies so moving, which are invisible to us owing to the interposition of the earth. This, they say, accounts for the fact that eclipses of the moon are more frequent than eclipses of the sun; for in addition to the earth each of these moving bodies can obstruct it. Indeed, as in any case the earth is not actually a centre but distant from it a full hemisphere, there is no more difficulty, they think, in accounting for the phenomena on their view that we do not dwell at the centre, than on the view that the earth is in the middle. Even as it is, there is nothing to suggest that we are removed from the centre by half the diameter of the earth. Others, again, say that the earth, which lies at the centre, is rolled, and thus in motion, about the axis of the whole heaven. So it stands written in the *Timaeus*.

There are similar disputes about the *shape* of the earth. Some think it is spherical, others that it is flat and drum-shaped. For evidence they bring the fact that, as the sun rises and sets, the part concealed by the earth shows a straight and not a curved edge, whereas if the earth were spherical the line of section would have to be circular. In this they leave out of account the great distance of the sun from the earth and the great size of the circumference, which, seen from a distance on these apparently small circles appears straight. Such an appearance ought not to make them doubt the circular shape of the earth. But they have another argument. They say that because it is at rest, the earth must necessarily have this shape.

There are many different ways in which the movement or rest of the earth has been conceived. The difficulty must have occurred to every one. It would indeed be a complacent mind that felt no surprise that, while a little bit of earth, let loose in mid-air, moves and will not stay still, and the more there is of it the faster it moves, the whole earth, free in mid-air, should show no movement at all. Yet here is this great weight of earth, and it is at rest. And again, from beneath one of these moving fragments of earth, before it falls, take away the earth, and it will continue its downward movement with nothing to stop it. The difficulty then, has naturally passed into a commonplace of philosophy; and one may well wonder that the solutions offered are not seen to involve greater absurdities than the problem itself.

By these considerations some, like Xenophanes of Colophon, have been led to assert that the earth below us is infinite, [saying that it has 'pushed its roots to infinity'] in order to save the trouble of seeking for the cause. Hence the sharp rebuke of Empedocles, in the words 'if the deeps of the earth are endless and endless the ample ether – such is the vain tale told by many a tongue, poured from the mouths of those who have seen but little of the whole'. Others say the earth rests upon water. This, indeed, is the oldest theory that has been preserved, and is attributed to Thales of Miletus. It was supposed to stay still because it floated like wood and other similar substances, which are so constituted as to rest upon water but not upon air. As if the same account had not to be given of the water which carries the earth as of the earth itself! It is not the nature of water, any more than of earth, to stay in mid-air: it must have something to rest upon. Again, as air is lighter than water, so is water than earth: how then can they think that the naturally lighter substance lies below the heavier? Again, if the earth as a whole is capable of floating upon water, that must obviously be the case with any part of it. But observation shows that this is not the case. Any piece of earth goes to the bottom, the quicker the larger it is. These thinkers seem to push their inquiries some way into the problem, but not so far as they might. It is what we are all inclined to do, to direct our inquiry not to the matter itself, but to the views of our opponents; for even when inquiring on one's own one pushes the inquiry only to the point at which one can no longer offer any opposition. Hence a good inquirer will be one who is ready in bringing forward the objections proper to the genus, and that he will be when he has gained an understanding of all the differences.

[. . .]

[. . .] There are some, Anaximander, for instance, among the ancients, who say that the earth keeps its place because of its indifference. Motion upward and downward and sideways were all, they thought, equally inappropriate to that which is set at the centre and indifferently related to every extreme point; and to move in contrary directions at the same time was impossible: so it must needs remain still. This view is ingenious but not true. The argument would prove that everything which is put at the centre must stay there. Fire, then, will rest at the centre; for the proof turns on no peculiar property of earth. But in any case it is superfluous. The observed facts about earth are not only that it remains at the centre, but also that it moves to the centre. The place to which any fragment of earth moves must necessarily be the place to which the whole moves; and in the place to which a thing naturally moves, it will naturally rest. The reason then is not in the fact that the earth is indifferently related to every extreme point; for this would apply to any body, whereas movement to the centre is peculiar to earth. Again it is absurd to look for a reason why the earth remains at the centre and not for a reason why fire remains at the extremity. If the extremity is the natural place of fire, clearly earth must also have a natural place. But suppose that the centre is not its place, and that the reason of its remaining there is this necessity of indifference – on the analogy of the hair which, it is said, however great the tension, will not break under it, if it be evenly distributed, or of the man who, though exceedingly hungry and thirsty, and both equally, yet being equidistant from food and drink, is therefore bound to stay where he is – even so, it still remains to explain why fire stays at the extremities. It is strange, too, to ask about things staying still but not about their motion, – why, I mean, one thing, if nothing stops it, moves up, and another thing to the centre. Again, their statements are not true. It happens, indeed, to be the case that a thing to which movement this way and that is equally inappropriate is obliged to remain at the centre. But so far as their argument goes, instead of remaining there, it will move, only not as a mass but in fragments. For the argument applies equally to fire. Fire, if set at the centre, should stay there, like earth, since it will be indifferently related to every point on the extremity. Nevertheless it will move, as in fact it always does move when nothing stops it, away from the centre to the extremity. It will not, however, move in a mass to a single point on the circumference – the only possible result on the lines of the indifference theory – but rather each corresponding portion of fire to the corresponding part of the extremity, each fourth part, for instance, to a fourth part of the circumference. For since no body is a point, it will have parts. The expansion, when the body increased the place occupied, would be on the same principle as the contraction, in which the place was diminished. Thus, for all the indifference theory shows to the contrary, the earth also would have moved in this manner away from the centre, unless the centre had been its natural place.

We have now outlined the views held as to the shape, position, and rest or movement of the earth.

14 Let us first decide the question whether the earth moves or is at rest. For, as we said, there are some who make it one of the stars, and others who, setting it at the centre, suppose it to be rolled and in motion about the pole as axis. That both views are untenable will be clear if we take as our starting-point the fact that the earth's motion, whether the earth be at the centre or away from it, must needs be a constrained motion. It cannot be the movement of the earth itself. If it were, any portion of it would have this movement; but in fact every part moves in a straight line to the centre. Being, then, constrained and unnatural, the movement could not be eternal. But the order of the universe is eternal. Again, everything that moves with the circular movement, except the first sphere, is observed to be passed, and to move with more than one motion. The earth, then, also, whether it moves about the centre or is stationary at it, must necessarily move with two motions. But if this were so, there would have to be passings and turnings of the fixed stars. Yet no such thing is observed. The same stars always rise and set in the same parts of the earth.

Further, the natural movement of the earth, part and whole alike, is to the centre of the whole – whence the fact that it is now actually situated at the centre – but it might be questioned, since both centres are the same, which centre it is that portions of earth and other heavy things move to. Is this their goal because it is the centre of the earth or because it is the centre of the whole? The goal, surely, must be the centre of the whole. For fire and other light things move to the extremity of the area which contains the centre. It happens, however, that the centre of the earth and of the whole is the same. Thus they do move to the centre of the earth, but accidentally, in virtue of the fact that the earth's centre lies at the centre of the whole. That the centre of the earth is the goal of their movement is indicated by the fact that heavy bodies moving towards the earth do not move parallel but so as to make equal angles, and thus to a single centre, that of the earth. It is clear, then, that the earth must be at the centre and immovable, not only for the reasons already given, but also because heavy bodies forcibly thrown quite straight upward return to the point from which they started, even if they are thrown to an unlimited distance. From these considerations then it is clear that the earth does not move and does not lie elsewhere than at the centre.

From what we have said the explanation of the earth's immobility is also apparent. If it is the nature of earth, as observation shows, to move from any point to the centre, as of fire contrariwise to move from the centre to the extremity, it is impossible that any portion of earth should move away from the centre except by constraint. For a single thing has a single movement, and a simple thing a simple: contrary movements cannot belong to the same thing, and movement away from the centre is the contrary of movement to it. If then no portion of earth can move away from the centre, obviously still less can the earth as a whole so move. For it is the nature of the whole to move to the point to which the part naturally moves. Since, then, it would require a force greater than itself to move it, it must needs stay at the centre. This view is further supported by the contributions of mathematicians to astronomy, since the phenomena – the changes of the shapes by which the order of the stars is determined – are fully accounted for on the hypothesis that the earth lies at the centre. Of the position of the earth and of the manner of its rest or movement, our discussion may here end.

Its shape must necessarily be spherical. For every portion of earth has weight until it reaches the centre, and the jostling of parts greater and smaller would bring about not a waved surface, but rather compression and convergence of part and part until the centre is reached. The process should be conceived by supposing the earth to come into being in the way that some of the natural philosophers describe. Only they attribute the downward movement to constraint, and it is better to keep to the truth and say that the reason of this motion is that a thing which possesses weight is naturally endowed with a centripetal movement. When the mixture, then, was merely potential, the things that were separated off moved similarly from every side towards the centre. Whether the parts which came together at the centre were distributed at the extremities evenly, or in some other way, makes no difference. If, on the one hand, there were a similar movement from each quarter of the extremity to the single centre, it is obvious that the resulting mass would be similar on every side. For if an equal amount is added on every side the extremity of the mass will be everywhere equidistant from its centre, i.e. the figure will be spherical. But neither will it in any way affect the argument if there is not a similar accession of concurrent fragments from every side. For the greater quantity, finding a lesser in front of it, must necessarily drive it on, both having an impulse whose goal is the centre, and the greater weight driving the lesser forward till this goal is reached. In this we have also the solution of a possible difficulty. The earth, it might be argued, is at the centre and spherical in shape: if, then, a weight many times that of the earth were added to one hemisphere, the centre of the earth and of the whole will no longer be coincident. So that either the earth will not stay at the centre, or if it does, it might even now be at rest without being at the centre but at a place where it is its nature to move. Such is the difficulty. A short consideration will give us an easy answer, if we first give precision to our postulate that any body endowed with weight, of whatever size, moves towards the centre. Clearly it will not stop when its edge touches the centre. The greater quantity must prevail until its own centre occupies the centre. For that is the goal of its impulse. Now it makes no difference whether we apply this to a clod or arbitrary fragment of earth or to the earth as a whole. The fact indicated does not depend upon degrees of size but applies universally to everything that has the centripetal impulse. Therefore earth in motion whether in a mass or in fragments, necessarily continues to move until it occupies the centre equally every way, the less being forced to equalize itself by the greater owing to the forward drive of the impulse.

If the earth was generated, then, it must have been formed in this way, and so clearly its generation was spherical; and if it is ungenerated and has remained so always, its character must be that which the initial generation, if it had occurred, would have given it. But the spherical shape, necessitated by this argument, follows also from the fact that the motions of heavy bodies always make equal angles, and are not parallel. This would be the natural form of movement towards what is naturally spherical. Either then the earth is spherical or it is at least naturally spherical. And it is right to call anything that which nature intends it to be, and which belongs to it, rather than that which it is by constraint and contrary to nature. The evidence of the senses further corroborates this. How else would eclipses of the moon show segments shaped as we see them? As it is, the shapes which the moon itself each month shows are of every kind – straight, gibbous, and concave – but in eclipses the outline is always curved; and, since it is the interposition of the earth that makes the eclipse, the form of this line will be caused by the form of the earth's surface, which is therefore spherical. Again, our observations of the stars make it evident, not only that the earth is circular, but also that it is a circle of no great size. For quite a small change of position on our part to south or north causes a manifest alteration of the horizon. There is much change, I mean, in the stars which are overhead, and the stars seen are different, as one moves northward or southward. Indeed there are some stars seen in Egypt and in the neighbourhood of Cyprus which are not seen in the northerly regions; and stars, which in the north are never beyond the range of observation, in those regions rise and set. All of which goes to show not only that the earth is circular in shape, but also that it is a sphere of no great size; for otherwise the effect of so slight a change of place would not be so quickly apparent. Hence one should not be too sure of the incredibility of the view of those who conceive that there is continuity between the parts about the pillars of Hercules and the parts about India, and that in this way the ocean is one. As further evidence in favour of this they quote the case of elephants, a species occurring in each of these extreme regions, suggesting that the common characteristic of these extremes is explained by their continuity. Also, those mathematicians who try to calculate the size of the earth's circumference arrive at the figure 400,000 stades. This indicates not only that the earth's mass is spherical in shape, but also that as compared with the stars it is not of great size.

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The Divisions of Nature and the Divisions of Knowledge

Aristotle

Aristotle was a keen observer of nature and had a great interest in unusual plants and animals. Knowing this, his pupil Alexander sent back to his old tutor unusual specimens of flora and fauna encountered on his military conquests. In this selection from the first book of *On the Parts of Animals*, Aristotle once again asks, and partly answers, fundamental questions: In order to learn about animals, should we examine them in classes or one by one as they come? What are the differences between the study of living things, such as a seed, and the study of abstract objects? How do the different sorts of causes give structure to our inquiry? How should one go about trying to grasp the real causes of things?

[. . .]

. . . Should one take each substantial being singly and define it independently, e.g. taking up one by one the nature of mankind, lion, ox, and any other animal as well; or should one first establish, according to something common, the attributes common to all? For many of the same attributes are present in many different kinds of animals, e.g. sleep, respiration, growth, deterioration, death, and in addition any remaining affections and dispositions such as these. (I add this because at the moment it is permissible to speak unclearly and indefinitely about these things.) It is apparent that, especially when speaking one by one, we shall repeatedly say the same things about many kinds; for instance, each of the attributes just mentioned belongs to horses, dogs, and human beings. So if one speaks of their attributes one by one, it will be necessary to speak repeatedly about the same things – whenever, that is, the same things are present in different forms of animal, yet themselves have no difference.

Yet there are probably other attributes which turn out to have the same predicate, but to differ by a difference in form, e.g. the locomotion of animals; it is apparent that locomotion is not one in form, because flying, swimming, walking,

From *Aristotle on the Parts of Animals*, trans. James G. Lennox (Oxford: Clarendon Press, 2001), pp. 1–8.

and crawling differ. Accordingly, the following question about how one is to carry out an examination should not be overlooked – I mean the question of whether one should study things in common according to kind first, and then later their distinctive characteristics, or whether one should study them one by one straight away. At present this matter has not been determined, nor has the question that will now be stated, namely, whether just as the mathematicians explain the phenomena in the case of astronomy, so the natural philosopher too, having first studied the phenomena regarding the animals and the parts of each, should then state the reason why and the causes, or whether he should proceed in some other way.

And in addition to these questions, since we see more than one cause of natural generation, e.g. both the cause for the sake of which and the cause from which comes the origin of motion, we need also to determine, about these causes, which sort is naturally first and which second. Now it is apparent that first is the one we call for the sake of which; for this is an account, and the account is an origin alike in things composed according to art and in things composed by nature. For once the doctor has defined health, and the builder has defined house, either by thought or perception, they provide the accounts and the causes of each of the things they produce, and the reason why it must be produced in this way. Yet that for the sake of which and the good are present more in the works of nature than in those of art.

What is of necessity is not present in all natural things in the same way; yet nearly everyone attempts to refer their accounts back to it without having distinguished in how many ways the necessary is said. That which is necessary without qualification is present in the eternal things, while that which is conditionally necessary is also present in all generated things, as it is in artefacts such as a house or any other such thing. It is necessary that a certain sort of matter be present if there is to be a house or any other end, and this must come to be and be changed first, then that, and so on continuously up to the end and that for the sake of which each comes to be and is. It is the same way too with things that come to be by nature.

However, the mode of demonstration and of necessity is different in natural science and the theoretical sciences. [. . .] For the origin is, in the latter cases, what is, but in the former, what will be. So: 'Since health or mankind is such, it is necessary for *this* to be or come to be', instead of 'Since *this* is or has come about, *that* from necessity is or will be'. Nor is it possible to connect the necessity in such a demonstration into eternity, as if to say, 'Since *this* is, therefore *that* is'. [. . .]

We should also not forget to ask whether it is appropriate to state, as those who studied nature before us did, how each thing has naturally come to be, rather than how it is. For the one differs not a little from the other. It seems we should begin, even with generation, precisely as we said before: first one should get hold of the phenomena concerning each kind, then state their causes. For even with house-building, it is rather that these things happen because the form of the house is such as it is, than that the house is such as it is because it comes to be in this way. For generation is for the sake of substantial being, rather than substantial being for the sake of generation. That is precisely why Empedocles misspoke when he said that many things are present in animals because of how things happened during generation – for example, that the backbone is such as it is because it happened to get broken through being twisted. He failed to understand, first, that seed already constituted with this sort of potential must be present, and second, that its producer was prior – not only in account but also in time. For one human being generates another; consequently, it is on account of *that* one being such as it is that *this* one's generation turns out a certain way. It is likewise both with things that seem to come to be spontaneously and with artefacts; for in some cases the same things produced by art also come to be spontaneously, e.g. health. Now in some of these cases there pre-exists a productive capacity like them, e.g. the art of sculpture; for a statue does not come to be spontaneously. The art is the account of the product without the matter. And it is likewise with the products of chance; for as the art has it, so they come to be.

Hence it would be best to say that, since this is what it is to be a human being, on account of this it has these things; for it cannot be without these parts. If one cannot say this, one should say the next best thing, i.e. either that in general it cannot be otherwise, or that at least it is good thus.

And these things follow. And since it is such, its generation necessarily happens in this way and is such as it is. (This is why this part comes to be first, then that one.) And in like manner one should speak in precisely this way about all of the things constituted by nature.

Now the ancients who first began philosophizing about nature were examining the material origin and that sort of cause: what matter is and what sort of thing it is, and how the whole comes to be from it and what moves it (e.g. whether strife, friendship, reason, or spontaneity). They also examined what sort of nature the underlying matter has of necessity, e.g. whether the nature of fire is hot, of earth cold, and whether the nature of fire is light, of earth heavy. In fact, even the cosmos they generate in this way. And they speak in a like manner too of the generation of animals and plants, saying, for example, that as water flowed into the body a stomach and every part that receives nourishment and residue came to be; and as the breath passed through, the nostrils were burst open.

Air and water are matter for bodies; that is, it is from such things that all the ancients constitute the nature of bodies. But if human beings, animals, and their parts exist by nature, one should speak about flesh, bone, blood, and all the uniform parts. Likewise too, about the non-uniform parts such as face, hand, and foot, one should say in virtue of what each of them is such as it is, and in respect of what sort of potential. For it is not enough to say from what things they are constituted, e.g. from fire or earth. It is just as if we were speaking about a bed or any other such thing; we would attempt to define its form rather than its matter, e.g. the bronze or the wood. And if we could not do this, we would at least attempt to define the matter of the composite; for a bed is a 'this-in-that' or 'this-such', so that we would have to mention its configuration as well, and what its visible character is. For the nature in respect of shape is more important than the material nature.

Now if it is by virtue of its configuration and colour that each of the animals and their parts is what it is, Democritus might be speaking correctly; for he appears to assume this. Note that he says it is clear to everyone what sort of thing a human being is in respect of shape, since it is known by way of its figure and its colour. And yet though the configuration of a corpse has the same shape, it is nevertheless *not* a human being. And further, it is impossible for something in any condition whatsoever, such as bronze or wooden, to be a hand, except homonymously (like a doctor in a picture). For such a hand will not be able to do its work, just as stone flutes will not be able to do theirs and the doctor in the picture his. Likewise none of the parts of a corpse is any longer such – I mean, for example, any longer an eye or a hand.

What Democritus has said, then, is too unqualified, and is said in the same way as a carpenter might speak about a wooden hand. Indeed this is also the way the natural philosophers speak of the generations and causes of configuration. Ask them by what potencies things were crafted. Well, no doubt the carpenter will say an axe or an auger, while the natural philosopher will say air and earth – albeit the carpenter's response is better; for it will be insufficient for him to say merely that when the tool fell this became a depression and that flat. Rather, he will state the cause, the reason why he made such a blow and for the sake of what, in order that it might then come to be this or that sort of shape.

It is clear, then, that these natural philosophers speak incorrectly. Clearly, one should state that the animal is of such a kind, noting about each of its parts what it is and what sort of thing it is, just as one speaks of the form of the bed. Suppose what one is thus speaking about is soul, or a part of soul, or is not without soul (at least when the soul has departed there is no longer an animal, nor do any of the parts remain the same, except in configuration, like those in myths that are turned to stone) – if these things are so, then it will be up to the natural philosopher to speak and know about the soul; and if not all of it, about that very part in virtue of which the animal is such as it is. He will state both what the soul or that very part of it is, and speak about the attributes it has in virtue of the sort of substantial being it is, especially since the nature of something is spoken of and is in two ways: as matter and as substantial being. And nature as substantial being is both nature as mover and nature as end. And it is the soul – either all of it or some part of it – that is such in the animal's case. So in this way too it will be requisite for the person studying nature to speak about soul more than the matter, inasmuch as it is more that the matter is nature because of soul than the reverse. And indeed, the wood is a bed or a stool because it is potentially these things.

In view of what was said just now, one might puzzle over whether it is up to natural science to speak about *all* soul, or some part, since if it speaks about all, no philosophy is left besides natural science. This is because reason is of the objects of reason, so that natural science would be knowledge about everything. For it is up to the same science to study reason and its objects, if they truly are correlative and the same study in every case attends to correlatives, as in fact is the case with perception and perceptible objects.

However, it is not the case that all soul is an origin of change, nor all its parts; rather, of growth the origin is the part which is present even in plants, of alteration the perceptive part, and of locomotion some other part, and not the rational; for locomotion is present in other animals too, but thought in none. So it is clear that one should not speak of all soul; for not all of the soul is a nature, but some part of it, one part or even more.

Further, none of the abstract objects can be objects of natural study, since nature does everything for the sake of something. For it is apparent that, just as in artefacts there is the art, so in things themselves there is an other sort of origin and cause, which we have as we do the hot and the cold – from the entire universe. This is why it is more likely that the heaven has been brought into being by such a cause – if it has come to be – and is due to such a cause, than that the mortal animals have been. Certainly the ordered and definite are far more apparent in the heavens than around us, while the fluctuating and random are more apparent in the mortal sphere. Yet some people say that each of the animals is and came to be by nature, while the heaven, in which there is not the slightest appearance of chance and disorder, was constituted in that way by chance and the spontaneous.

We say 'this is for the sake of that' whenever there appears to be some end towards which the change proceeds if nothing impedes it. So it is apparent that there is something of this sort, which is precisely what we call a nature. Surely it is not any chance thing that comes to be from each seed, nor a chance seed which comes from a chance body; rather, *this* one comes from *that* one. Therefore the seed is an origin and is productive of what comes from it. For these things are by nature; at least they grow from seed. But prior even to this is what the seed is the seed of; for while the seed is becoming, the end is being. And prior again to both of these is what the seed is from. For the seed is a seed in two ways, *from* which and *of* which; that is, it is a seed both of what it came from, e.g. from a horse, and it is a seed of what will be from it, e.g. of a mule, though not in the same way, but of each in the way mentioned. Further, the seed is in potentiality; and we know how potentiality is related to complete actuality.

Therefore there are these two causes, the cause for the sake of which and the cause from necessity; for many things come to be because it is a necessity. One might perhaps be puzzled about what sort of necessity those who say 'from necessity' mean; for it cannot be either of the two sorts defined in our philosophical discussions. But it is especially in things that partake of generation that the third sort is present; for we say nourishment is something necessary according to neither of those two sorts of necessity, but because it is not possible to be without it. And this is, as it were, conditionally necessary; for just as, since the axe must split, it is a necessity that it be hard, and if hard, then made of bronze or iron, so too since the body is an instrument (for each of the parts is for the sake of something, and likewise also the whole), it is therefore a necessity that it be of such a character and constituted from such things, if that is to be.

Clearly, then, there are two sorts of cause, and first and foremost one should succeed in stating both, but failing that, at least attempt to do so; and clearly all who do not state this say virtually nothing about nature. For nature is an origin more than matter. Even Empedocles occasionally stumbles upon this, led by the truth itself, and is forced to say that the substantial being and the nature is the account, e.g. when he says what bone is. He does not say that it is some one of the elements, or two or three, or all of them, but rather that it is an account of their mixture. Accordingly, it is clear that flesh too, and each of the other such parts, is what it is in the same way.

One reason our predecessors did not arrive at this way is that there was no 'what it is to be' and 'defining substantial being'. Democritus touched on this first, not however as necessary for the study of nature, but because he was carried away by the subject itself; while in Socrates' time interest in this grew, but research into the natural world ceased, and philosophers turned instead to practical virtue and politics.

One should explain in the following way, e.g. breathing exists for the sake of *this*, while *that* comes to be from necessity because of *these*. But 'necessity' sometimes signifies that if that – i.e. that for the sake of which – is to be, it is necessary for these things to obtain, while at other times it signifies that things are thus in respect of their character and nature. For it is necessary for the hot to go out and enter again upon meeting resistance, and for the air to flow in. This is directly necessary; and it is as the internal heat retreats during the cooling of the external air that inhalation and exhalation occur. This then is the way of investigation, and it is in relation to these things and things such as these that one should grasp the causes.

1.10

On Methods of Inference

Philodemus

Philodemus (c.110–c.40 BC) was an Epicurean philosopher and poet whose literary work influenced his famous pupil, Virgil. When the town of Herculaneum was flattened by the eruption of Vesuvius, it buried a villa containing a large number of papyri, flattening and carbonizing them but also embalming them. With infrared imaging and other techniques, we have now been able to recover much of the content of these scrolls. The fragment from Philodemus given here shows a surprisingly sophisticated appreciation of, and a surprisingly modern-sounding approach to, the problem of induction.

And further the Stoics err in so far as they have not taken the trouble to understand the right method of analogical inference. Whenever we say,

> Since things in our experience are of such a nature,
> Unperceived objects are also of this nature *in so far as* things in our experience are of this nature,

we judge that there is a necessary connection between an unperceived object and the objects of our experience. For example,

> Since men in our experience *as men* are mortal,
> If there are men anywhere,
> They are mortal.

There are four things that the words "as such," "according as," and "in so far as," signify; . . .

[Here Philodemus distinguishes four senses of these phrases.]

But those who attack the inference from analogy do not indicate the distinctions just mentioned, namely, howe we are to take the "according as," as in the statement, for example,

> Man as man is mortal.

From Phillip Howard DeLacy and Estell Allen DeLacy, "Philodemus: On Methods of Inference. A Study in Ancient Empiricism," *The American Journal of Philology* 68: 3 (1947): 321–2 (extracts).

Hence they say that if the "according as" is omitted, the argument will be inconclusive; if it is admitted, the method of contraposition is used. But we Epicureans take this to be necessarily connected with that from the fact that this has been observed to be a property of all cases that we have come upon, and because we have observed many varied living creatures of the same genus who have differences in all other respects from each other, but who all share in certain common qualities (e.g., mortality). According to this method we say that man according as and in so far as he is man is mortal, on the ground that we have examined systematically many diverse men, and have found no variation in respect to this characteristic and no evidence to the contrary . . .

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1.11
The Explanatory Power of Atomism

Lucretius

Lucretius (c.94–c.49 BC) was a Roman philosopher and poet whose great work *On the Nature of Things* provides the fullest and most detailed exposition of atomism in antiquity. Lucretius' analysis of physical phenomena from the atomistic perspective is powerful and persuasive, but like other atomists he extended the reduction beyond physics, claiming that not just the body but the soul could be accounted for wholly in terms of atoms and the void. As a consequence, atomists of the scientific revolution like Galileo, Boyle, and Hooke had to persuade their contemporaries that atomism and Christianity were compatible. This selection is from the first book of *On the Nature of Things*.

For what is to follow, my Memmius, lay aside your cares and lend undistracted ears and an attentive mind to true reason. Do not scornfully reject, before you have understood them, the gifts I have marshaled for you with zealous devotion. I will set out to discourse to you on the ultimate realities of heaven and the gods. I will reveal those *atoms* from which nature creates all things and increases and feeds them and into which, when they perish, nature again resolves them. To these in my discourse I commonly give such names as the 'raw material', or 'generative bodies' or 'seeds' of things. Or I may call them 'primary particles', because they come first and everything else is composed of them.

[. . .]

[O]ur starting-point will be this principle: *Nothing can ever be created by divine power out of nothing*. The reason why all mortals are so gripped by fear is that they see all sorts of things happening on the earth and in the sky with no discernible cause, and these they attribute to the will of a god. Accordingly, when we have seen that nothing can be created out of nothing, we shall

From *On the Nature of the Universe*, trans. R. E. Latham, revised with an introduction by John Goodwin (Penguin, 1951, 1994), from book 1, pp. 11, 13–27.

then have a clearer picture of the path ahead, the problem of how things are created and occasioned without the aid of the gods.

First then, if things were made out of nothing, any species could spring from any source and nothing would require seed. Men could arise from the sea and scaly fish from the earth, and birds could be hatched out of the sky. Cattle and other domestic animals and every kind of wild beast, multiplying indiscriminately, would occupy cultivated and wastelands alike. The same fruits would not grow constantly on the same trees, but they would keep changing: any tree might bear any fruit. If each species were not composed of its own generative bodies, why should each be born always of the same kind of mother? Actually, since each is formed out of specific seeds, it is born and emerges into the sunlit world only from a place where there exists the right material, the right kind of atoms. This is why everything cannot be born of everything, but a specific power of generation inheres in specific objects.

Again, why do we see roses appear in spring, grain in summer's heat, grapes under the spell of autumn? Surely, because it is only after specific seeds have drifted together at their own proper time that every created thing stands revealed, when the season is favorable and the life-giving earth can safely deliver delicate growths into the sunlit world. If they were made out of nothing, they would spring up suddenly after varying lapses of time and at abnormal seasons, since there would of course be no primary bodies which could be prevented by the harshness of the season from entering into generative unions. Similarly, in order that things might grow, there would be no need of any lapse of time for the accumulation of seed. Tiny tots would turn suddenly into grown men, and trees would shoot up spontaneously out of the earth. But it is obvious that none of these things happens, since everything grows gradually, as is natural, from a specific seed and retains its specific character. It is a fair inference that each is increased and nourished by its own raw material.

Here is a further point. Without seasonable showers the earth cannot send up gladdening growths. Lacking food, animals cannot reproduce their kind or sustain life. This points to the conclusion that many elements are common to many things, as letters are to words, rather than to the theory that anything can come into existence without atoms.

[. . .]

The second great principle is this: *nature resolves everything into its component atoms and never reduces anything to nothing*. If anything were perishable in all its parts, anything might perish all of a sudden and vanish from sight. There would be no need of any force to separate its parts and loosen their links. In actual fact, since everything is composed of indestructible seeds, nature obviously does not allow anything to perish till it has encountered a force that shatters it with a blow or creeks into chinks and unknits it.

If the things that are banished from the scene by age are annihilated through the exhaustion of their material, from what source does Venus bring back the several races of animals into the light of life? And, when they are brought back, where does the inventive earth find for each the special food required for its sustenance and growth? From what fount is the sea replenished by its native springs and the streams that flow into it from afar? Whence does the ether draw nutriment for the stars? For everything consisting of a mortal body must have been exhausted by the long day of time, the illimitable past. If throughout this bygone eternity there have persisted bodies from which the universe has been perpetually renewed, they must certainly be possessed of immortality. Therefore things cannot be reduced to nothing.

Again, all objects would regularly be destroyed by the same force and the same cause, were it not that they are sustained by imperishable matter more or less tightly fastened together. Why, a mere touch would be enough to bring about destruction supposing there were no imperishable bodies whose union could be dissolved only by the appropriate force. Actually, because the fastenings of the atoms are of various kinds while their matter is imperishable, compound objects remain intact until one of them encounters a force that proves strong enough to break up its particular constitution. Therefore nothing returns to nothing, but everything is resolved into its constituent bodies. . . .

Well, Memmius, I have taught you that things cannot be created out of nothing nor, once born, be summoned back to nothing. Perhaps, however, you are becoming mistrustful of my words, because these atoms of mine are not visible to the eye. Consider, therefore, this further evidence of *bodies whose existence you must acknowledge though they cannot be seen*. First, wind, when its force is roused, whips up waves, founders tall ships and scatters clouds. Sometimes scouring plains with hurricane force it strews them with huge trees and batters mountain peaks with blasts that hew down forests. Such is wind in its fury, when it whoops aloud with a mad menace in its shouting. Without question, therefore, there must be invisible particles of wind that sweep sea, that sweep land, that sweep the clouds in the sky, swooping upon them and whirling them along in a headlong hurricane. In the way they flow and the havoc they spread they are no different from a torrential flood of water when it rushes down in a sudden spate from the mountain heights, swollen by heavy rains, and heaps together wreckage from the forest and entire trees. Soft though it is by nature, the sudden shock of oncoming water is more than even stout bridges can withstand, so furious is the force with which the turbid, storm-flushed torrent surges against their piers. With a mighty roar it lays them low, rolling huge rocks under its waves and brushing aside every obstacle from its course. Such, therefore, must be the movement of blasts of wind also. When they have come surging along some course like a rushing river, they push obstacles before them and buffet them with repeated blows; and sometimes, eddying round and round, they snatch them up and carry them along in a swiftly circling vortex. Here then is proof upon proof that winds have invisible bodies, since in their actions and behavior they are found to rival great rivers, whose bodies are plain to see.

Then again, we smell the various scents of things though we never see them approaching our nostrils. Similarly, we do not look upon scorching heat nor can we grasp cold in our eyes and we do not see sounds. Yet all these must be composed of physical bodies, since they are able to impinge upon our senses. For nothing can touch or be touched except bodies.

Again, clothes hung out on a surf-beaten shore grow moist. Spread in the sun they grow dry. But we do not see how the moisture has soaked into them, nor again how it has been dispelled by the heat. It follows that the moisture is split up into minute parts which the eye cannot possibly see.

Again, in the course of many annual revolutions of the sun a ring is worn thin next to the finger with continual rubbing. Dripping water hollows a stone. A curved ploughshare, iron though it is, dwindles imperceptibly in the furrow. We see the cobblestones of the highway worn by the feet of many wayfarers. The bronze statues by the city gates show their right hands worn thin by the touch of travelers who have greeted them in passing. We see that all these are being diminished, since they are worn away. But to perceive what particles drop off at any particular time is a power grudged to us by our ungenerous sense of sight.

To sum up, whatever is added to things gradually by nature and the passage of days, causing a cumulative increase, eludes the most attentive scrutiny of our eyes. Conversely, you cannot see what objects lose by the wastage of age – sheer sea cliffs, for instance, exposed to prolonged erosion by the mordant brine – or at what time the loss occurs. It follows that nature works through the agency of invisible bodies.

On the other hand, things are not hemmed in by the pressure of solid bodies in a tight mass. This is because *there is vacuity in things*. A grasp of this fact will be helpful to you in many respects and will save you from much bewildered doubting and questioning about the universe and from mistrust of my teaching. Well then, by vacuity I mean intangible and empty space. If it did not exist, things could not move at all. For the distinctive action of matter, which is counteraction and obstruction, would be in force always and everywhere. Nothing could move forward, because nothing would give it a starting-point by receding. As it is, we see with our eyes at sea and on land and high up in the sky that all sorts of things in all sorts of ways are on the move. If there were no empty space, these things would be denied the power of restless movement – or rather, they could not possibly have come into existence, embedded as they would have been in motionless matter.

Besides, there are clear indications that things that pass for solid are in fact porous. Even in rocky caves a trickle of water seeps through, and every surface weeps with brimming drops. Food percolates to every part of an animal's body. Trees grow and pour forth their fruit in season, because their food is distributed throughout their length from the tips of the roots through the trunk and along every branch. Noises pass through walls and fly into closed buildings. Freezing cold penetrates to the bones. If there were no vacancies through which the various bodies could make their way, none of these phenomena would be possible.

Again, why do we find some things outweigh others of equal volume? If there is as much matter in a ball of wool as in one of lead, it is natural that it should weigh as heavily, since it is the function of matter to press everything downwards, while it is the function of space on the other hand to remain weightless. Accordingly, when one thing is not less bulky than another but obviously lighter, it plainly declares that there is more vacuum in it, while the heavier object proclaims that there is more matter in it and much less empty space. We have therefore reached the goal of our diligent enquiry: there is in things an admixture of what we call vacuity.

[. . .]

To pick up the thread of my discourse, all nature as it is in itself consists of two things – bodies and the vacant space in which the bodies are situated and through which they move in different directions. The existence of bodies is vouched for by the agreement of the senses. If a belief resting directly on this foundation is not valid, there will be no standard to which we can refer any doubt on obscure questions for rational confirmation. If there were no place and space, which we call vacuity, these bodies could not be situated anywhere or move in any direction whatever. This I have just demonstrated. It remains to show that nothing exists that is distinct both from body and from vacuity and could be ranked with the others as a third substance. For whatever is must also be something. If it offers resistance to touch, however light and slight, it will increase the mass of body by such amount, great or small, as it may amount to, and will rank with it. If, on the other hand, it is intangible, so that it offers no resistance whatever to anything passing through it, then it will be that empty space which we call vacuity. Besides, whatever it may be in itself, either it will act in some way, or react to other things acting upon it, or else it will be such that things can be and happen in it. But without body nothing can act or react; and nothing can afford a place except emptiness and vacancy. Therefore, besides matter and vacuity, we cannot include in the number of things any third substance that can either affect our senses at any time or be grasped by the reasoning of our minds.

You will find that anything that can be named is either a property or an accident of these two. A property is something that cannot be detached or separated from a thing without destroying it, as weight is a property of rocks, heat of fire, fluidity of water, tangibility of all bodies, intangibility of vacuum. On the other hand, servitude, poverty and riches, freedom, war, peace and all other things whose advent or departure leaves the essence of a thing intact, all these it is our practice to call by their appropriate name, accidents.

Similarly, time by itself does not exist; but from things themselves there results a sense of what has already taken place, what is now going on and what is to ensue. It must not be claimed that anyone can sense time by itself apart from the movement of things or their restful immobility.

[. . .]

Material objects are of two kinds, atoms and compounds of atoms. The atoms themselves cannot be swamped by any force, for they are preserved indefinitely by their absolute solidity. Admittedly, it is hard to believe that anything can exist that is absolutely solid. The lightning stroke from the sky penetrates closed buildings, as do shouts and other noises. Iron glows white-hot in the fire, and rocks crack in savage scorching heat. Hard gold is softened and melted by heat; and the ice of bronze is liquefied by flame. Both heat and piercing cold seep through silver, since we feel both alike when a cooling shower of water is poured into a goblet that we hold ceremonially in our hands. All these facts point to the conclusion that nothing is really solid. But sound reasoning and nature itself drive us to the opposite conclusion. Pay attention, therefore, while I demonstrate in a few lines that there exist certain bodies that are absolutely solid and indestructible, namely those atoms which according to our teaching are the seeds of prime units of things from which the whole universe is built up.

In the first place, we have found that nature is twofold, consisting of two totally different things, matter and the space in which things happen. Hence each of these must exist by itself without admixture of the other. For, where there is empty space (what we call vacuity), there matter is not; where matter exists, there cannot be a vacuum. Therefore the prime units of matter are solid and free from vacuity.

Again, since composite things contain some vacuum, the surrounding matter must be solid. For you cannot reasonably maintain that anything can hide vacuity and hold it within its body unless you allow that the container itself is solid. And what contains the vacuum in things can only be an accumulation of matter. Hence matter, which possesses absolute solidity, can be everlasting when other things are decomposed.

Again, if there were no empty space, everything would be one solid mass; if there were no material objects with the property of filling the space they occupy, all existing space would be utterly void. It is clear, then, that there is an alternation of matter and vacuity, mutually distinct, since the whole is neither completely full nor completely empty. There are therefore solid bodies, causing the distinction between empty space and full. And these, as I have just shown, can be neither decomposed by blows from without nor invaded and unknit from within nor destroyed by any other form of assault. For it seems that a thing without vacuum can be neither knocked to bits nor snapped nor chopped in two by cutting; nor can it let in moisture or seeping cold or piercing fire, the universal agents of destruction. The more vacuum a thing contains within it, the more readily it yields to these assailants. Hence, if the units of matter are solid and without vacuity, as I have shown, they must be everlasting.

Yet again, if the matter in things had not been everlasting, everything by now would have gone back to nothing, and the things we see would be the product of rebirth out of nothing. But, since I have already shown that nothing can be created out of nothing nor any existing thing be summoned back to nothing, the atoms must be made of imperishable stuff into which everything can be resolved in the end, so that there may be a stock of matter for building the world anew. The atoms, therefore, are absolutely solid and unalloyed. In no other way could they have survived throughout infinite time to keep the world renewed.

Furthermore, if nature had set no limit to the breaking of things, the particles of matter in the course of ages would have been ground so small that nothing could be generated from them so as to attain from them in the fullness of time to the summit of its growth. For we see that anything can be more speedily disintegrated than put together again. Hence, what the long day of time, the bygone eternity, has already shaken and loosened to fragments could never in the residue of time be reconstructed. As it is, there is evidently a limit set to breaking, since we see that everything is renewed and each according to its kind has a fixed period in which to grow to its prime.

Here is a further argument. Granted that the particles of matter are absolutely solid, we can still explain the composition and behavior of soft things – air, water, earth, fire – by their intermixture with empty space. On the other hand, supposing the atoms to be soft, we cannot account for the origin of hard flint and iron. For there would be no foundation for nature to build on. Therefore there must be bodies strong in their unalloyed solidity by whose closer clustering things can be knit together and display unyielding toughness.

If we suppose that there is no limit set to the breaking of matter, we must still admit that material objects consist of particles which throughout eternity have resisted the forces of destruction. To say that these are breakable does not square with the fact that they have survived throughout eternity under a perpetual bombardment of innumerable blows.

Again, there is laid down for each thing a specific limit to its growth and its tenure of life, and the laws of nature ordain what each can do and what it cannot. No species is ever changed, but each remains so much itself that every kind of bird displays on its body its own specific markings. This is a further proof that their bodies are made of changeless matter. For, if the atoms could yield in any way to change, there would be no certainty as to what could arise and what could not, at what point the power of everything was limited by an immovable frontier post; nor could successive generations so regularly repeat the nature, behavior, habits and movements of their parents.

To proceed with our argument, there is an ultimate point in visible objects that represents the smallest thing that can be seen. So also there must be an ultimate point in objects that lie below the limit of perception by our senses. This point is without parts and is the smallest thing that can exist. It never has been and never will be able to exist by itself, but only as one primary part of something else. It is with a mass of such parts, solidly jammed together in formation, that matter is filled up. Since they cannot exist by themselves, they must needs stick together in a mass from which they cannot by any means be prized loose. The atoms, therefore, are absolutely solid and unalloyed, consisting of a mass of least parts tightly packed together. They are not compounds formed by the coalescence of their parts, but bodies of absolute and everlasting solidity. To these nature allows no loss or diminution, but guards them as seeds for things. If there are no such least parts, even the smallest bodies consist of an infinite number of parts, since they can always be halved and their halves halved again without limit. On this showing, what difference will there be between the whole universe and the very least of things? None at all. For, however endlessly infinite the universe may be, yet the smallest things will equally consist of an infinite number of parts. Since true reason cries out against this and denies that the mind can believe it, you must needs give in and admit that there are least parts which themselves are partless. Granted that these parts exist, you must needs admit that the atoms they compose are also solid and everlasting. But, if all things were compelled by all-creating nature to be broken up into these least parts, nature would lack the power to rebuild anything out of them. For partless objects cannot have the essential properties of generative matter – those varieties of attachment, weight, impetus, impact and movement on which everything depends.

[. . .]

The truth, as I maintain, is this: there are certain bodies whose impacts, movements, order, position and shapes produce fires. When their order is changed, they change their nature. In themselves they do not resemble fire or anything else that can bombard our senses with particles or impinge on our organs of touch.

To say, as Heraclitus does, that everything is fire, and nothing can be numbered among things as a reality except fire, seems utterly crazy. On the basis of the senses he attacks and unsettles the senses – the foundation of all belief and the only source of his knowledge of that which he calls fire. He believes that the senses clearly perceive fire, but not the other things that are in fact no less clear. This strikes me as not only pointless but mad. For what is to be our standard of reference? What can be a surer guide to the distinction of true from false than our own senses?

1.12

The Earth: Its Size, Shape, and Immobility

Claudius Ptolemy

Ptolemy (c.90–c.168) was a Roman astronomer whose major work, usually referred to by the title of its Arabic translation as the *Almagest*, provides a computationally workable model of the solar system in which the earth is motionless near (but not quite at) the center of the sun's orbit while the sun, moon, and other planets travel around the earth. The *Almagest* was the definitive treatise on astronomy through the Middle Ages until Copernicus. In this selection from the first book of the *Almagest*, Ptolemy argues that the earth is spherical, that in relation to the distance of the fixed stars it is so small that it should be considered to be a mere geometric point, and that it does not move.

The Heavens Move Like a Sphere

It is plausible to suppose that the ancients got their first notions on these topics from the following kind of observations. They saw that the sun, moon, and other stars moved from east to west along circular paths which were always parallel to each other, that they started by rising up from below the earth itself as it were, gradually achieving their ascent, and then kept circling in the same way and getting lower, until, seeming to fall to earth, they vanished completely. Then, after remaining invisible for some time, they rose and set once more. And they saw that the intervals between these motions, and also the locations of the rising and setting, were on the whole determined and regular.

The main phenomenon that led them to the idea of a sphere was the revolution of the ever-visible stars. They observed that this revolution was circular as well as continuous about a single common center. Naturally they considered that point to be the pole of the heavenly sphere. For they saw that the closer were stars to that point,

From *The Book of the Cosmos*, ed. Dennis Richard Danielson (Cambridge, MA: Perseus, 2000), extracts from pp. 69–74. Adapted from Claudius Ptolemy, *Almagest*, trans. G. J. Toomer (New York: Springer-Verlag, 1984).

the smaller were their circles. And the farther were stars from it, the greater were their circles – right out to the limit where stars became invisible. But here too they saw that some heavenly bodies near the ever-visible stars remained visible for only a short time, while some farther away remained invisible for a long time, again depending on how far away they were from the pole. So they arrived at the idea of the heavenly sphere merely from this kind of inference. But from then on, in subsequent investigations, they found that everything else fit with this notion, and that absolutely all appearances contradicted any alternative notion that was proposed.

For suppose that the stars' motion takes place in a straight line towards infinity, as some have thought. How then could one explain their appearing to set out from the same starting-point every day? How could the stars return if their motion were towards infinity? Or, if they did return, would not the straight-line hypothesis be obviously wrong? For according to it, the stars would gradually have to diminish in size until they disappeared, whereas in fact they appear greater at the very moment of their disappearance, at which point they are obstructed and cut off, as it were, by the earth's surface.

It is also absurd to imagine the stars ignited as they rise out of the earth and extinguished again as they fall to earth. Just suppose that the strict order in their size and number, their intervals, positions, and periods could be restored by such a random and chance process, and that one whole region of earth has igniting properties, and another has extinguishing properties – or rather that the same region ignites stars for one set of observers and extinguishes them for another set, and that the same stars are already ignited or extinguished for some observers while they are not yet for others! Even on this ridiculous supposition, what could we say about the ever-visible stars, which neither rise nor set? The stars that are ignited and extinguished ought to rise and set for observers everywhere, while those that are not ignited and extinguished should always be visible to observers everywhere. How would we explain the fact that this is not so? We can hardly say that stars that are ignited and extinguished for some observers never undergo this process for other observers. Yet it is utterly obvious that the very same stars that rise and set in certain regions of the earth neither rise nor set in other regions.

Finally, to assume any motion at all other than spherical motion would entail that the distances of stars measured from the earth upwards must vary, regardless of where or how we assume the earth itself is situated. Hence the apparent sizes of the stars and the distances between them would necessarily vary for the same observers during the course of each revolution, for their distances from the objects of observation would be now greater, now lesser. Yet we see that no such variation occurs. And the apparent increase in their sizes at the horizon is caused not by a decrease in their distances but by the exhalations of moisture surrounding the earth. These intervene between the place from which we observe and the heavenly bodies. In the same way, objects placed in water appear bigger than they really are, and the lower they sink, the bigger they appear.

[. . .]

The Earth Too, Taken as a Whole, is Sensibly Spherical

That the earth, too, taken as a whole, is sensibly spherical can best be grasped from the following considerations. To repeat, we see that the sun, moon, and other stars do not rise and set simultaneously for everyone on earth, but do so earlier for those towards the east and later for those towards the west. And eclipses, especially lunar eclipses, take place simultaneously for all observers yet are not recorded by all observers as occurring at the same *hour* (that is, at an equal distance from noon). Rather, the hour recorded by observers in the east is always later than that recorded by those in the west. And we find that the differences in the recorded hour are proportional to the distances between the places of observation. Hence, one can reasonably conclude that the earth's surface is spherical, because its evenly curving surface (for so it is when considered as a whole) cuts off the heavenly bodies for each set of observers in a manner that is gradual and regular.

This would not happen if the earth's shape were other than spherical, as one can see from the following arguments. If the shape were concave, the stars would be seen rising first by those more towards the west; if it were a plane, they would rise and set simultaneously for everyone on earth; if it were triangular or square or any other polygonal shape, similarly they would rise and set simultaneously for all those living on the same planar surface. Yet clearly nothing like this takes place. Nor could the earth be cylindrical, with the curved surface in the east–west direction, and the flat sides towards the poles of the universe, as some might suppose more plausible. For to those living on the curved surface none of the stars would be ever-visible. Either all stars would rise and set for all observers, or the same stars, for an equal celestial distance from each of the poles, would always be invisible for all observers. In fact, however, the further we travel toward the north, the more of the southern stars disappear and the more of the northern stars become visible. Clearly, then, here too the curvature of the earth cuts off the heavenly bodies in a regular fashion in a north–south direction and demonstrates the sphericity of the earth in all directions.

Moreover, if we sail towards mountains or elevated places from whatever direction, north, south, east or west, we observe them to increase gradually in size as if rising up from the sea itself in which they had previously been submerged. This is due to the curvature of the surface of the water.

The Earth Has the Ratio of a Point to the Heavens

The earth has, to the senses, the ratio of a point to the distance of the sphere of the so-called fixed stars. This is strongly indicated by the fact that the sizes and distances of the stars at any given time appear equal and the same from any and every place on earth. Observations of the same celestial objects from different latitudes are found to have not the least discrepancy from each other. Moreover, gnomons set up in any part of the earth whatever, and likewise the centers of armillary spheres, operate like the real center of the earth. . . .

Another clear demonstration of the above proposition is that a plane drawn through the observer's line of sight at any point on earth – we call this plane one's "horizon" – always bisects the whole heavenly sphere. This would not happen if the earth were of perceptible size in relation to the distance of the heavenly bodies. In that case only the plane drawn through the center of the earth could exactly bisect the sphere, and a plane through any point on the surface of the earth would always make the section of the heavens below the plane greater than the section above it.

Neither Does the Earth have Any Motion from Place to Place

One can show by arguments like the one above that the earth can have no motion in the directions mentioned, nor indeed can it ever move at all from its position at the center. For if it did move, the same phenomena would result as those that would follow from its having any position other than the central one. To me it seems pointless, therefore, to ask why objects move towards the center of the earth, once it has been so clearly established from actual phenomena that the earth occupies the middle place in the universe, and that all heavy objects are carried towards that place. The following fact alone amply supports this claim. Absolutely everywhere on the face of the earth – which has been shown to be spherical and in the middle of the universe – the direction and path of the motion (I mean proper, natural motion) of all heavy bodies is everywhere consistently at right angles to the plane that is tangent to the point of impact on the earth's surface. Clearly, therefore, if these falling objects were not stopped by the earth's surface, they would certainly reach the center of the earth itself, since any line drawn through the center of a sphere is always perpendicular to the tangent plane at the line's point of intersection with the sphere's surface.

Those who think it paradoxical that the earth, having such great weight, is not supported by anything and yet does not move, seem to me to be making the mistake of judging on the basis of their own experience instead of taking into account the peculiar nature of the universe. They would not, I think, consider this fact strange if they realized that the magnitude of the earth, when compared with the whole surrounding mass of the universe, has the ratio of a point to it. Given this way of thinking, it will seem quite consistent that (relatively speaking) the smallest of things should be overpowered and pressed in equally from all directions to a position of equilibrium by the greatest of things (which possess a uniform nature). For there is no up and down in the universe with respect to itself, any more than "up" and "down" make sense within a sphere. Rather, in the universe, the proper and natural motion of compound bodies is as follows: light and rarefied bodies drift outwards towards the circumference, but seem to move in the direction which is "up" for each observer, since the overhead direction for all of us, which we also call "up," points towards the surrounding surface. Heavy and dense bodies, on the contrary, are carried towards the middle and the center, but seem to fall downwards, again because the line of movement towards our feet, which we call "down," also points towards the center of the earth. These heavy bodies, as one would expect, settle about the center because of their mutual pressure and resistance, which is equal and uniform from all directions. For the same reason it is plausible that the earth, since its total mass is so great compared with the bodies which fall towards it, can remain motionless under the impact of these very small weights (for they strike it from all sides), and receive, as it were, the objects that fall upon it. . . .

Certain people, however, propose what they consider to be a more convincing model. They do not disagree with what I have said above, since they have no argument to bring against it. But they think no evidence prevents them from supposing, for example, that the heavens remain motionless and that the earth revolves from west to east about the same axis, making approximately one revolution each day. Or they suppose that both heaven and earth move by some amount, each about the same axis and in such a way as to preserve the overtaking of one by the other. However, they do not realize that, although there is perhaps nothing in the celestial phenomena to count against that simpler hypothesis, nevertheless what would occur here on earth and in the air would render such a notion quite ridiculous.

For the sake of argument, let us suppose that, contrary to nature, the most rare and light matter should either be motionless or else move in exactly the same way as matter with the opposite nature. . . . Suppose, too, that the densest and heaviest objects have a proper motion of the quick and uniform kind which they suppose (although, again, as everyone knows, earthly objects are sometimes not readily moved even by an external force). Even granted this supposition, they would have to admit that the revolving motion of the earth must be the most violent of all the motions they postulate, given that the earth makes one revolution in such a short time. Accordingly, all objects not actually standing on the earth would appear to have the same motion, opposite to that of the earth: neither clouds nor other flying or thrown objects would ever be seen moving towards the east, since the earth's motion towards the east would always outrun and overtake them, so that all other objects would seem to move backwards towards the west. Even if they claim chat the air is carried around in the same direction and with the same speed as the earth, still the compound objects in the air would always seem to be left behind by the motion of both earth and air together. Or, if those objects too were carried around, fused as it were to the air, then they would never appear to have any motion either forwards or backwards. They would always appear still, neither wandering about nor changing position, whether they were things in flight or objects thrown. Yet we quite plainly see that they do undergo all these kinds of motion in such a way that they are not even slowed down or speeded up at all by any motion of the earth.

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1.13

The Weaknesses of the Hypotheses

Proclus

Proclus (c.410–485), one of the last of the Greek Neoplatonist philosophers, wrote commentaries on several of Plato's dialogues and on the first book of Euclid's *Elements*. His work was influential on subsequent philosophical and scientific thought, not least among Arab philosophers. In this selection from his *Hypotyposis astronomicarum positionum*, Proclus expresses skepticism about the physical reality of the epicycles that astronomers following Ptolemy used to account for the apparent motions of the planets. His complaint that the Ptolemaic account lacks unity was revived over a millennium later by Copernicus, who called the Ptolemaic system monstrous; and his charge that astronomers have derived the causes of natural movements from something that does not exist in nature comes up again in the work of Kepler.

My dear friend: The great Plato thinks that the real philosopher ought to study the sort of astronomy that deals with entities more abstract than the visible heaven, without reference to either sense perception or ever-changing matter. In that world of abstract entities he will come to know slowness itself and speed itself in their true numerical relationships. Now, I think, you wish to bring us down from that contemplation of abstract truth to consideration of the orbits on the visible heaven, to the observations of professional astronomers and to the hypotheses which they have devised from these observations, hypotheses which people like Aristarchus, Hipparchus, Ptolemy and others like them are always writing about. I suppose you want to become acquainted with their theories because you wish to examine carefully all the theories, as far as that is possible, with which the ancients, in their speculations about the universe, have abundantly supplied us.

Last year, when I was staying with you in central Lydia, I promised you that when I had time,

From Proclus, "Hypotyposis astronomicarum positionum," trans. A. Wasserstein, in *Physical Thought from the Presocratics to the Quantum Physicists*, ed. Shmuel Sambursky (London: Hutchinson, 1974).

I would work with you on these matters in my accustomed way. Now that I have arrived in Athens and heaven has freed me from those many unending troubles, I keep my promise to you and will . . . explain to you the real truth which those who are so eager to contemplate the heavenly bodies have come to believe by means of long and, indeed, endless chains of reasoning. In doing so I must, of course, pretend to myself to forget, for the moment at any rate, Plato's exhortations and the theoretical explanations which he taught us to maintain. Even so, I shall not be able to refrain from applying, as is my habit, a critical mind to their doctrines, though I shall do so sparingly, since I am convinced that the exposition of their doctrines will suggest to you quite clearly what the weaknesses of their hypotheses are, hypotheses of which they are so proud when developing their theories.

Before I end, I wish to add this: in their endeavor to demonstrate that the movements of the heavenly bodies are uniform, the astronomers have unwittingly shown the nature of these movements to be lacking in uniformity and to be the subject of outside influences. What shall we say of the eccentrics and the epicycles of which they speak so much? Are they only conceptual notions or do they have a substantial existence in the spheres with which they are connected? If they exist only as concepts, then the astronomers have passed, without noticing it, from bodies really existing in nature to mathematical notions and, again without noticing it, have derived the causes of natural movements from something that does not exist in nature. I will add further that there is absurdity also in the way in which they attribute particular kinds of movement to heavenly bodies. That we conceive of these movements, that is not proof that the stars which we conceive of moving in these circles really move anomalously.

On the other hand, if the astronomers say that the circles have a real, substantial existence, then they destroy the coherence of the spheres themselves on which the circles are situated. They attribute a separate movement to the circles and another to the spheres, and again, the movement they attribute to the circles is not the same for all of them; indeed, sometimes these movements take place in opposite directions. They vary the distances between them in a confused way; sometimes the circles come together in one plane, at other times they stand apart, and cut each other. There will, therefore, be all sorts of divisions, foldings and separations.

I want to make this further observation: the astronomers exhibit a very casual attitude in their exposition of these hypothetical devices. Why is it that, on any given hypothesis, the eccentric or, for that matter, the epicycle moves (or is stationary) in such and such a way while the star moves either in direct or retrograde motion? And what are the explanations (I mean the real explanations) of those planes and their separations? This they never explain in a way that would satisfy our yearning for complete understanding. They really go backwards: they do not derive their conclusions deductively from their hypotheses, as one does in the other sciences; instead, they attempt to formulate the hypotheses starting from the conclusions, which they ought to derive from the hypotheses. It is clear that they do not even solve such problems as could well be solved.

One must, however, admit that these are the simplest hypotheses and the most fitting for divine bodies, and that they have been constructed with a view to discovering the characteristic movements of the planets (which, in real truth, move in exactly the same way as they *seem* to move) and to formulating the quantitative measures applicable to them.

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1.14

Projectile Motion

John Philoponus

John Philoponus (c.490–c.570), sometimes called John of Alexandria or John the Grammarian, was a Christian philosopher, scientist, and theologian who lived and worked in Alexandria. Though he was trained as a Neoplatonist by one of Proclus's students, he broke in fundamental ways with the Neoplatonic tradition. His work influenced Arab philosophers such as Avempace (Ibn Bajja), the medieval philosopher-scientists Buridan and Oresme, and Galileo. In the following selection from his commentary on Aristotle's *Physics*, Philoponus mercilessly critiques Aristotle's suggested account of projectile motion and introduces the idea of *impetus*, an "incorporeal motive force," as a more plausible explanation.

Such, then, is Aristotle's account in which he seeks to show that forced motion and motion contrary to nature could not take place if there were a void. But to me this argument does not seem to carry conviction. For in the first place really nothing has been adduced, sufficiently cogent to satisfy our minds, to the effect that motion contrary to nature or forced motion is caused in one of the ways enumerated by Aristotle. . . .

For in the case of *antiperistasis* [the process whereby P_1 pushes P_2 into P_3's place, P_2 pushes P_3 into P_4's place, . . . , P_{n-1} pushes P_n into P_1's place] there are two possibilities; (1) the air that has been pushed forward by the projected arrow or stone moves back to the rear and takes the place of the arrow or stone, and being thus behind it pushes it on, the process continuing until the impetus of the missile is exhausted, or, (2) it is not the air pushed ahead but the air from the sides that takes the place of the missile. . . .

Let us suppose that *antiperistasis* takes place according to the first method indicated above, namely, that the air pushed forward by the arrow gets to the rear of the arrow and thus pushes it from behind. On that assumption, one would be hard put to it to say what it is (since

From Morris R. Cohen and I. E. Drabkin (eds.), *A Source Book in Greek Science* (Cambridge, Mass.: Harvard University Press, 1966), pp. 221–3.

there seems to be no counter force) that causes the air, once it has been pushed forward, to move back, that is along the sides of the arrow, and, after it reaches the rear of the arrow, to turn around once more and push the arrow forward. For, on this theory, the air in question must perform three distinct motions: it must be pushed forward by the arrow, then move back, and finally turn and proceed forward once more. Yet air is easily moved, and once set in motion travels a considerable distance. How, then, can the air, pushed by the arrow, fail to move in the direction of the impressed impulse, but instead, turning about, as by some command, retrace its course? Furthermore, how can this air, in so turning about, avoid being scattered into space, but instead impinge precisely on the notched end of the arrow and again push the arrow on and adhere to it? Such a view is quite incredible and borders rather on the fantastic.

Again, the air in front that has been pushed forward by the arrow is, clearly, subjected to some motion, and the arrow, too, moves continuously. How, then, can this air, pushed by the arrow, take the place of the arrow, that is, come into the place which the arrow has left? For before this air moves back, the air from the sides of the arrow and from behind it will come together and, because of the suction caused by the vacuum, will instantaneously fill up the place left by the arrow, particularly so the air moving along with the arrow from behind it. Now one might say that the air pushed forward by the arrow moves back and pushes, in its turn, the air that has taken the place of the arrow, and thus getting behind the arrow pushes it into the place vacated by the very air pushed forward (by the arrow) in the first instance. But in that case the motion of the arrow would have to be discontinuous. For before the air from the sides, which has taken the arrow's place, is itself pushed, the arrow is not moved. For this air does not move it. But if, indeed, it does, what need is there for the air in front to turn about and move back? And in any case, how or by what force could the air that had been pushed forward receive an impetus for motion in the opposite direction? . . .

So much, then, for the argument which holds that forced motion is produced when air takes the place of the missile (*antiperistasis*). Now there is a second argument which holds that the air which is pushed in the first instance [i.e. when the arrow is first discharged] receives an impetus to motion, and moves with a more rapid motion than the natural [downward] motion of the missile, thus pushing the missile on while remaining always in contact with it until the motive force originally impressed on this portion of air is dissipated. This explanation, though apparently more plausible, is really no different from the first explanation by *antiperistasis*, and the following refutation will apply also to the explanation by *antiperistasis*.

In the first place we must address the following questions to those who hold the views indicated: "When one projects a stone by force, is it by pushing the air behind the stone that one compels the latter to move in a direction contrary to its natural direction? Or does the thrower impart a motive force to the stone, too?" Now if he does not impart any such force to the stone, but moves the stone merely by pushing the air, and if the bowstring moves the arrow in the same way, of what advantage is it for the stone to be in contact with the hand, or for the bowstring to be in contact with the notched end of the arrow?

For it would be possible, without such contact, to place the arrow at the top of a stick, as it were on a thin line, and to place the stone in a similar way, and then, with countless machines, to set a large quantity of air in motion behind these bodies. Now it is evident that the greater the amount of air moved and the greater the force with which it is moved the more should this air push the arrow or stone, and the further should it hurl them. But the fact is that even if you place the arrow or stone upon a line or point quite devoid of thickness and set in motion all the air behind the projectile with all possible force, the projectile will not be moved the distance of a single cubit

If, then, the air, though moved with a greater force [than that used by one who hurls a projectile], could not impart motion to the projectile, it is evident, in the case of the hurling of missiles or the shooting of arrows, it is not the air set in motion by the hand or bowstring that produces the motion of the missile or arrow. For why would such a result be any more likely when the projector is in contact with the projectile than when he is not? And, again, if the arrow is in direct contact with the bowstring and the stone with the hand, and there is nothing between, what air behind the projectile could be moved? If it is the air from the sides that is moved, what has that to do with the projectile? For that air falls outside the [trajectory of the] projectile.

From these considerations and from many others we may see how impossible it is for forced motion to be caused in the way indicated. Rather is it necessary to assume that some incorporeal motive force is imparted by the projector to the projectile, and that the air set in motion contributes either nothing at all or else very little to this motion of the projectile. If, then, forced motion is produced as I have suggested, it is quite evident that if one imparts motion "contrary to nature" or forced motion to an arrow or a stone the same degree of motion will be produced much more readily in a void than in a plenum. And there will be no need of any agency external to the projector. . . .

1.15

Free Fall

John Philoponus

In the following selection, which is also taken from his commentary on Aristotle's *Physics*, Philoponus critiques Aristotle's account of free fall. Unlike Aristotle, Philoponus takes seriously the physical possibility of there being a void and asks how an object might move in a void. Where Aristotle's remarks suggest that (within limits) he is relating force, velocity and resistance in a way we might be tempted to express as $V \propto F/R$, Philoponus' analysis suggests something like $V \propto F - R$. Though neither expression is correct by modern standards, Philoponus' critique of Aristotle's position represents a definite conceptual advance since it does not lead to absurd consequences when resistance goes to zero.

Weight, then, is the efficient cause of downward motion, as Aristotle himself asserts. This being so, given a distance to be traversed, I mean through a void where there is nothing to impede motion, and given that the efficient cause of the motion differs [i.e., that there are differences in weight], the resultant motions will inevitably be at different speeds, even through a void. . . . Clearly, then, it is the natural weights of bodies, one having a greater and another a lesser downward tendency, that causes differences in motion. For that which has a greater downward tendency divides a medium better. Now air is more effectively divided by a heavier body. To what other cause shall we ascribe this fact than that that which has greater weight has, by its own nature, a greater downward tendency, even if the motion is not through a plenum? . . .

And so, if a body cuts through a medium better by reason of its greater downward tendency, then, even if there is nothing to be cut, the body will none the less retain its greater downward tendency. . . . And if bodies possess a greater or a lesser downward tendency in and of themselves, clearly they will possess this difference in themselves even if they move through a void. The

From Morris R. Cohen and I. E. Drabkin (eds.), *A Source Book in Greek Science* (Cambridge, Mass.: Harvard University Press, 1966), pp. 217–21.

same space will consequently be traversed by the heaver body in shorter time and by the lighter body in longer time, even though the space be void. The result will be due not to greater or lesser interference with the motion [i.e. the resistance of the medium, since in a void there is none] but to the greater or lesser downward tendency, in proportion to the natural weight of the bodies in question. . . .

Sufficient proof has been adduced to show that if motion took place through a void, it would not follow that all bodies would move therein with equal speed. We have also shown that Aristotle's attempt to prove that they would so move does not carry conviction. Now if our reasoning up to this point has been sound it follows that our earlier proposition is also true, namely, that it is possible for motion to take place through a void in finite time. . . .

Thus, if a certain time is required for each weight, in and of itself, to accomplish a given motion, it will never be possible for one and the same body to traverse a given distance, on one occasion through a plenum and on another through a void, in the same time.

For if a body moves the distance of a stade through air, and the body is not at the beginning and at the end of the stade at one and the same instant, a definite time will be required, dependent on the particular nature of the body in question, for it to travel from the beginning of the course to the end (for, as I have indicated, the body is not at both extremities at the same instant), and this would be true even if the space traversed were a void. But a certain *additional time* is required because of the interference of the medium. For the pressure of the medium and the necessity of cutting through it make the motion through it more difficult.

Consequently, the thinner we conceive the air to be through which a motion takes place, the less will be the *additional time* consumed in dividing the air. And if we continue indefinitely to make this medium thinner, the additional time will also be reduced indefinitely, since time is indefinitely divisible. But even if the medium be thinned out indefinitely in this way, the total time consumed will never be reduced to the time which the body consumes in moving the distance of a stade through the void. I shall make my point clearer by examples.

If a stone moves the distance of a stade through a void, there will necessarily be a time, let us say an hour, which the body will consume in moving the given distance. But if we suppose this distance of a stade filled with water, no longer will the motion be accomplished in one hour, but a certain additional time will be necessary because of the resistance of the medium. Suppose that for the division of the water another hour is required, so that the same weight covers the distance through a void in one hour and through water in two. Now if you thin out the water, changing it into air, and if air is half as dense as water, the time which the body has consumed in dividing the water will be proportionately reduced. In the case of water the additional time was an hour. Therefore the body will move the same distance through air in an hour and a half [i.e., the hour it would take to go through a void, plus half an hour (half as much as the hour that would be added to pass through water) because air offers only half the resistance of water]. If, again, you make the air half as dense [as you already did], the motion will be accomplished in an hour and a quarter. And if you continue indefinitely to rarefy the medium, you will decrease indefinitely the time required for the division of the medium, for example, the additional hour required in the case of water. But you will bever completely eliminate this additional time, for time is indefinitely divisible.

If, then, by rarefying the medium you will never eliminate this additional time, and if in the case of motion through a plenum there is always some portion of the second hour to be added, in proportion to the density of the medium, clearly the stade will never be traversed by a body through a void in the same time as through a plenum. . . .

But it is completely false and contrary to the evidence of experience to argue as follows: "If a stade is traversed through a plenum in two hours, and through a void in one hour, then if I take a medium half as dense as the first, the same distance will be traversed through this rarer medium in half the time, that is, in one hour: hence the same distance will be traversed through a plenum in the same time as through a void." *For Aristotle wrongly assumes that the ratio of the times required for motion through various media is equal to the ratio of the densities of the media. . . .*

Now this argument of Aristotle's seems convincing and the fallacy is not easy to detect because it is impossible to find the ratio which air bears to water, in its composition, that is, to find how much denser water is than air, or one specimen of air than another. But from a consideration of the moving bodies themselves we are able to refute Aristotle's contention. [Philoponus spends the rest of this paragraph drawing out a consequence of Aristotle's view before attacking it in the next paragraph.] For if, in the case of one and the same body moving through two different media, the ratio of the times required for the motions were equal to the ratio of the densities of the respective media, then, since differences of velocity are determined not only by the media but also by the moving bodies themselves, the following proposition would be a fair conclusion: "in the case of bodies differing in weight and moving through one and the same medium, the ratio of the times required for the motions is equal to the inverse ratio of the weights." For example, if the weight were doubled, the time would be halved. That is, if a weight of two pounds moved the distance of a stade through the air in one-half hour, a weight of one pound would move the same distance in one hour. Conversely, the ratio of the weights of the bodies would have to be equal to the inverse ratio of the times required for the motions.

But this is completely erroneous, and our view may be corroborated by actual observation more effectively than by any sort of verbal argument. *For if you let fall from the same height two weights of which one is many times as heavy as the other, you will see that the ratio of the times required for the motion does not depend on the ratio of the weights, but that the difference in time is a very small one*. And so, if the difference in the weights is not considerable, that is, of one is, let us say, double the other, there will be no difference, or else an imperceptible difference, in time, though the difference in weight is by no means negligible, with one body weighing twice as much as the other.

Now if, in the case of different weights in motion through the same medium, the ratio of the times required for the motions is not equal to the inverse ratio of the weights, and, conversely, the ratio of the weights is not equal to the inverse ratio of the times, the following proposition would surely be reasonable: "If identical bodies move through different media, like air and water, the ratio of the times required for the motions through the air and water, respectively, is not equal to the ratio of the densities of air and water, and conversely."

Now if the ratio of the times is not determined by the ratio of the densities of the media, it follows that a medium half as dense will not be traversed in half the time, but longer than half. Furthermore, as I have indicated above, in proportion as the medium is rarefied, the shorter is the *additional* time required for the division of the medium. But this additional time is never completely eliminated; it is merely decreased in proportion to the degree of rarefaction of the medium, as has been indicated. . . . And so, if the *total* time required is not reduced in proportion to the degree of rarefaction of the medium, and if the time added for the division of the medium is diminished in proportion to the rarefaction of the medium, but never entirely eliminated, it follows that a body will never traverse the same distance through a plenum in the same time as through a void.

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1.16

Against the Reality of Epicycles and Eccentrics

Moses Maimonides

Moses Maimonides (1135–1204), was arguably the greatest Jewish thinker of the Middle Ages and made fundamental contributions to rabbinical doctrine as well as to philosophy. In this selection from Book II, chapter 24 of his *Guide of the Perplexed*, he addresses the question of the physical reality of the equants and epicycles used in Ptolemaic astronomy. Maimonides rejects these devices as incompatible with Aristotle's physics, which he considers to be firmly established. But he is perplexed by the fact that an astronomy constructed using these fictitious devices is empirically accurate.

You know of astronomical matters what you have read under my guidance and understood from the contents of the "Almagest." But there was not enough time to begin another speculative study with you. What you know already is that as far as the action of ordering the motions and making the course of the stars conform to what is seen is concerned, everything depends on two principles: either that of the epicycles or that of the eccentric spheres or on both of them. Now I shall draw your attention to the fact that both those principles are entirely outside the bounds of reasoning and opposed to all that has been made clear in natural science. In the first place, if one affirms as true the existence of an epicycle revolving round a certain sphere, positing at the same time that that revolution is not around the center of the sphere carrying the epicycles – and this has been supposed with regard to the moon and to the five planets – it follows necessarily that there is rolling, that is, that the epicycle rolls and changes its place completely. Now this is the impossibility that was to be avoided, namely, the assumption that there should be something in the heavens that changes its place. For this reason Abu Bakr Ibn al-Saigh states in his extant discourse on astronomy that the existence of epicycles is impossible. He points out the necessary inference already mentioned. In addition to this impossibility necessarily following from the assumption

The Guide of the Perplexed, Vol. 1, trans. Shlomo Pines (Chicago: University of Chicago Press, 1963). Reprinted with permission from The University of Wisconsin Press.

of the existence of epicycles, he sets forth there other impossibilities that also follow from that assumption. I shall explain them to you now.

The revolution of the epicycles is not around the center of the world. Now it is a fundamental principle of this world that there are three motions: a motion from the midmost point of the world, a motion toward that point, and a motion around that point. But if an epicycle existed, its motion would be neither from that point nor toward it nor around it.

Furthermore, it is one of the preliminary assumptions of Aristotle in natural science that there must necessarily be some immobile thing around which circular motion takes place. Hence it is necessary that the earth should be immobile. Now if epicycles exist, theirs would be a circular motion that would not revolve round an immobile thing. I have heard that Abu Bakr has stated that he had invented an astronomical system in which no epicycles figured, but only eccentric circles. However, I have not heard this from his pupils. And even if this were truly accomplished by him, he would not gain much thereby. For eccentricity also necessitates going outside the limits posed by the principles established by Aristotle, those principles to which nothing can be added. It was by me that attention was drawn to this point. In the case of eccentricity, we likewise find that the circular motion of the spheres does not take place around the midmost point of the world, but around an imaginary point that is other than the center of the world. Accordingly, that motion is likewise not a motion taking place around an immobile thing. If, however, someone having no knowledge of astronomy thinks that eccentricity with respect to these imaginary points may be considered – when these points are situated inside the sphere of the moon, as they appear to be at the outset – as equivalent to motion round the midmost point of the world, we would agree to concede this to him if that motion took place round a point in the zone of fire or of air, though in that case that motion would not be around an immobile thing. We will, however, make it clear to him that the measures of eccentricity have been demonstrated in the "Almagest" according to what is assumed there. And the latter-day scientists have given a correct demonstration, regarding which there is no doubt, of how great the measure of these eccentricities is compared with half the diameter of the earth, just as they have set forth all the other distances and dimensions. It has consequently become clear that the eccentric point around which the sun revolves must of necessity be outside the concavity of the sphere of the moon and beneath the convexity of the sphere of Mercury. Similarly the point around which Mars revolves, I mean to say the center of its eccentric sphere, is outside the concavity of the sphere of Mercury and beneath the convexity of the sphere of Venus. Again the center of the eccentric sphere of Jupiter is at the same distance – I mean between the sphere of Mercury and Venus. As for Saturn, the center of its eccentric sphere is between the spheres of Mars and Jupiter. See now how all these things are remote from natural speculation! All this will became clear to you if you consider the distances and dimensions, known to you, of every sphere and star, as well as the evaluation of all of them by means of half the diameter of the earth so that everything is calculated according to one and the same proportion and the eccentricity of every sphere is not evaluated in relation to the sphere itself.

Even more incongruous and dubious is the fact that in all cases in which one of two spheres is inside the other and adheres to it on every side, while the centers of the two are different, the smaller sphere can move inside the bigger one without the latter being in motion, whereas the bigger sphere cannot move upon any axis whatever without the smaller one being in motion. For whenever the bigger sphere moves, it necessarily, by means of its movement, sets the smaller one in motion, except in the case in which its motion is on an axis passing through the two centers. From this demonstrative premise and from the demonstrated fact that vacuum does not exist and from the assumptions regarding eccentricity, it follows necessarily that when the higher sphere is in motion it must move the sphere beneath it with the same motion and around its own center. Now we do not find that this is so. We find rather that neither of the two spheres, the containing and the contained, is set in motion by the movement of the other nor does it move around the other's center or poles, but that each of them has its own particular motion. Hence necessity obliges the belief that between every two spheres there are bodies other than those of the spheres. Now if this be so, how many obscure points remain? Where will you suppose the centers of those bodies existing between every two spheres to be? And those bodies should likewise have their own particular motion. Thabit has explained this in a treatise of his and has demonstrated what we have said, namely, that there must be the body of a sphere between every two spheres. All this I did not explain to you when you read under my guidance, for fear of confusing you with regard to that which it was my purpose to make you understand.

As for the inclination and deviation that are spoken of regarding the latitude of Venus and Mercury, I have explained to you by word of mouth and I have shown you that it is impossible to conceive their existence in those bodies. For the rest Ptolemy has said explicitly, as you have seen, that one was unable to do this, stating literally: No one should think that these principles and those similar to them may only be put into effect with difficulty, if his reason for doing this be that he regards that which we have set forth as he would regard things obtained by artifice and the subtlety of art and which may only be realized with difficulty. For human matters should not be compared to those that are divine. This is, as you know, the text of his statement. I have indicated to you the passages from which the true reality of everything I have mentioned to you becomes manifest, except for what I have told you regarding the examination of where the points lie that are the centers of the eccentric circles. For I have never come across anybody who has paid attention to this. However this shall become clear to you through the knowledge of the measure of the diameter of every sphere and what the distance is between the two centers as compared with half the diameter of the earth, according to what has been demonstrated by al-Qabisi in the "Epistle concerning the Distances." If you examine those distances, the truth of the point to which I have drawn your attention will become clear to you.

Consider now how great these difficulties are. If what Aristotle has stated with regard to natural science is true, there are no epicycles or eccentric circles and everything revolves round the center of the earth. But in that case how can the various motions of the stars come about? Is it in any way possible that motion should be on the one hand circular, uniform, and perfect, and that on the other hand the things that are observable should be observed in consequence of it, unless this be accounted for by making use of one of the two principles or of both of them? This consideration is all the stronger because of the fact that if one accepts everything stated by Ptolemy concerning the epicycle of the moon and its deviation toward a point outside the center of the world and also outside the center of the eccentric circle, it will be found that what is calculated on the hypothesis of the two principles is not at fault by even a minute. The truth of this is attested by the correctness of the calculations – always made on the basis of these principles – concerning the eclipses and the exact determination of their times as well as of the moment when it begins to be dark and of the length of time of the darkness. Furthermore, how can one conceive the retrogradation of a star, together with its other motions, without assuming the existence of an epicycle? On the other hand, how can one imagine a rolling motion in the heavens or a motion around a center that is not immobile? This is the true perplexity.

However, I have already explained to you by word of mouth that all this does not affect the astronomer. For his purpose is not to tell us in which way the spheres truly are, but to posit an astronomical system in which it would be possible for the motions to be circular and uniform and to correspond to what is apprehended through sight, regardless of whether or not things are thus in fact. You know already that in speaking of natural science, Abu Bakr Ibn al-Sa'igh expresses a doubt whether Aristotle knew about the eccentricity of the sun and passed over it in silence – treating of what necessarily follows from the sun's inclination, inasmuch as the effect of eccentricity is not distinguishable from that of inclination – or whether he was not aware of eccentricity. Now the truth is that he was not aware of it and had never heard about it, for in his time mathematics had not been brought to perfection. If, however, he had heard about it, he would have violently rejected it; and if it were to his mind established as true, he would have become most perplexed about all his assumptions on the subject. I shall repeat here what I have said before. All that Aristotle states about that which is beneath the sphere of the moon is in accordance with reasoning; these are things that have a known cause, that follow one upon the other, and concerning which it is clear and manifest at what points wisdom and natural providence are effective. However, regarding all that is in the heavens, man grasps nothing but a small measure of what is mathematical; and you know what is in it. I shall accordingly say in the manner of poetical preciousness: *The heavens are the heavens of the Lord, but the earth hath He given to the sons of man*. I mean thereby that the deity alone fully knows the true reality, the nature, the substance, the form, the motions, and the causes of the heavens. But He has enabled man to have knowledge of what is beneath the heavens, for that is his world and his dwelling-place in which he has been placed and of which he himself is a part. This is the truth. For it is impossible for us to accede to the points starting from which conclusions may be drawn about the heavens; for the latter are too far away from us and too high in place and in rank. And even the general conclusion that may be drawn from them, namely, that they prove the existence of their Mover, is a matter the knowledge of which cannot be reached by human intellects. And to fatigue the minds with notions that cannot be grasped by them and for the grasp of which they have no instrument, is a defect in one's inborn disposition or some sort of temptation. Let us then stop at a point that is within our capacity, and let us give over the things that cannot be grasped by reasoning to him who was reached by the mighty divine overflow so that it could be fittingly said of him: *With him do I speak mouth to mouth.* That is the end of what I have to say about this question. It is possible that someone else may find a demonstration by means of which the true reality of what is obscure for me will become clear to him. The extreme predilection that I have for investigating the truth is evidenced by the fact that I have explicitly stated and reported my perplexity regarding these matters as well as by the fact that I have not heard nor do I know a demonstration as to anything concerning them.

1.17

Impetus and Its Applications

Jean Buridan

Jean Buridan (1300–c.1358) was one of the great philosophers of the high Middle Ages. In this selection from his *Questions on the Eight Books of Aristotle's Physics*, Buridan criticizes Aristotle's theory of projectile motion by appealing our experience of common objects such as a top, a lance, and a ship – a method of persuasion that Galileo subsequently adopts. Picking up on the suggestion made by John Philoponus, Buridan develops a theory of impressed force, which he calls *impetus*, to account for the continued motion of an object when it is no longer in contact with the body that set it in motion. Such a theory, he claims, fits the appearances. Yet Buridan is somewhat tentative in his conclusion because he has arrived at it only by showing the inadequacy of the alternatives others have advanced.

Book viii, Question 12

1 It is sought whether a projectile after leaving the hand of the projector is moved by the air, or by what it is moved.

It is argued that it is not moved by the air, because the air seems rather to resist, since it is necessary that it be divided. Furthermore, if you say that the projector in the beginning moved the projectile and the ambient air along with it, and then that air, having been moved, moves the projectile further to such and such a distance, the doubt will return as to by what the air is moved after the projector ceases to move. For there is just as much difficulty regarding this (the air) as there is regarding the stone which is thrown.

Aristotle takes the opposite position in the eighth [book] of this work (the *Physics*) thus: "Projectiles are moved further after the projectors are no longer in contact with them, either by antiperistasis, as some say, or by the fact that the air having been pushed, pushes with a movement swifter than the movement of impulsion by which it (the body) is carried towards its own

From Marshall Clagett, *The Science of Mechanics in the Middle Ages* (Madison, WI: University of Wisconsin Press, 1959), pp. 532–8. © 1959. Reprinted with permission from the University of Wisconsin Press.

[natural] place." He determines the same thing in the seventh and eighth [books] of this work (the *Physics*) and in the third [book] of the *De caelo.*

2 This question I judge to be very difficult because Aristotle, as it seems to me, has not solved it well. For he touches on two opinions. The first one, which he calls "antiperistasis," holds that the projectile swiftly leaves the place in which it was, and nature, not permitting a vacuum, rapidly sends air in behind to fill up the vacuum. The air moved swiftly in this way and impinging upon the projectile impels it along further. This is repeated continually up to a certain distance. . . . But such a solution notwithstanding, it seems to me that this method of proceeding was without value because of many experiences (*experientie*).

The first experience concerns the top (*trocus*) and the smith's mill (i.e. wheel – *mola fabri*) which are moved for a long time and yet do not leave their places. Hence, it is not necessary for the air to follow along to fill up the place of departure of a top of this kind and a smith's mill. So it cannot be said [that the top and the smith's mill are moved by the air] in this manner.

The second experience is this: A lance having a conical posterior as sharp as its anterior would be moved after projection just as swiftly as it would be without a sharp conical posterior. But surely the air following could not push a sharp end in this way, because the air would be easily divided by the sharpness.

The third experience is this: a ship drawn swiftly in the river even against the flow of the river, after the drawing has ceased, cannot be stopped quickly, but continues to move for a long time. And yet a sailor on deck does not feel any air from behind pushing him. He feels only the air from the front resisting [him]. Again, suppose that the said ship were loaded with grain or wood and a man were situated to the rear of the cargo. Then if the air were of such an impetus that it could push the ship along so strongly, the man would be pressed very violently between that cargo and the air following it. Experience shows this to be false. Or, at least, if the ship were loaded with grain or straw, the air following and pushing would fold over (*plico*) the stalks which were in the rear. This is all false.

3 Another opinion, which Aristotle seems to approve, is that the projector moves the air adjacent to the projectile [simultaneously] with the projectile and that air moved swiftly has the power of moving the projectile. He does not mean by this that the same air is moved from the place of projection to the place where the projectile stops, but rather that the air joined to the projector is moved by the projector and that air having been moved moves another, part of the air next to it, and that [part] moves another (i.e., the next) up to a certain distance. Hence the first air moves the projectile into the second air, and the second [air moves it] into the third air, and so on. Aristotle says, therefore, that there is not one mover but many in turn. Hence he also concludes that the movement is not continuous but consists of succeeding or contiguous entities.

But this opinion and method certainly seems to me equally as impossible as the opinion and method of the preceding view. For this method cannot solve the problem of how the top or smith's mill is turned after the hand [which sets them into motion] has been removed. Because, if you cut off the air on all sides near the smith's mill by a cloth (*linteamine*), the mill does not on this account stop but continues to move for a long time. Therefore it is not moved by the air.

Also a ship drawn swiftly is moved a long time after the haulers have stopped pulling it. The surrounding air does not move it, because if it were covered by a cloth and the cloth with the ambient air were withdrawn, the ship would not stop its motion on this account. And even if the ship were loaded with grain or straw and were moved by the ambient air, then that air ought to blow exterior stalks toward the front. But the contrary is evident, for the stalks are blown rather to the rear because of the resisting ambient air.

Again, the air, regardless of how fast it moves, is easily divisible. Hence it is not evident as to how it would sustain a stone of weight of one thousand pounds projected in a sling or in a machine.

Furthermore, you could, by pushing your hand, move the adjacent air, if there is nothing in your hand, just as fast or faster than if you were holding in your hand a stone which you wish to project. If, therefore, that air by reason of the velocity of its motion is of a great enough impetus to move the stone swiftly, it seems that if I were to impel air toward you equally as fast, the air ought to push you impetuously and with sensible strength. [Yet] we would not perceive this.

Also, it follows that you would throw a feather farther than a stone and something less heavy farther than something heavier, assuming equal magnitudes and shapes. Experience shows this to be false. The consequence is manifest, for the air having been moved ought to sustain or carry or move a feather more easily than something heavier. . . .

4 Thus we can and ought to say that in the stone or other projectile there is impressed something which is the motive force (*virtus motiva*) of that projectile. And this is evidently better than falling back on the statement that the air continues to move that projectile. For the air appears rather to resist. Therefore, it seems to me that it ought to be said that the motor in moving a moving body impresses (*imprimit*) in it a certain impetus (*impetus*) or a certain motive force (*vis motiva*) of the moving body, [which impetus acts] in the direction toward which the mover was moving the moving body, either up or down, or laterally, or circularly. *And by the amount the motor moves that moving body more swiftly, by the same amount it will impress in it a stronger impetus.* It is by that impetus that the stone is moved after the projector ceases to move. But that impetus is continually decreased (*remittitur*) by the resisting air and by the gravity of the stone, which inclines. It in a direction contrary to that in which the impetus was naturally predisposed to move it. Thus the movement of the stone continually becomes slower, and finally that impetus is so diminished or corrupted that the gravity of the stone wins out over it and moves the stone down to its natural place.

This method, it appears to me, ought to be supported because the other methods do not appear to be true and also because all the appearances (*apparentia*) are in harmony with this method.

5 For if anyone seeks why I project a stone farther than a feather, and iron or lead fitted to my hand farther than just as much wood, I answer that the cause of this is that the reception of all forms and natural dispositions is in matter and by reason of matter. *Hence by the amount more there is of matter, by that amount can the body receive more of that impetus and more intensely* (intensius). *Now in a dense and heavy body, other things being equal, there is more of prime matter than in a rare and light one. Hence a dense and heavy body receives more of that impetus and more intensely, just as iron can receive more calidity than wood or water of the same quantity.* Moreover, a feather receives such an impetus so weakly (*remisse*) that such an impetus is immediately destroyed by the resisting air. *And so also if light wood and heavy iron of the same volume and of the same shape are moved equally fast by a projector, the iron will be moved farther because there is impressed in it a more intense impetus, which is not so quickly corrupted as the lesser impetus would be corrupted. This also is the reason why it is more difficult to bring to rest a large smith's mill which is moving swiftly than a small one, evidently because in the large one, other things being equal, there is more impetus.* And for this reason you could throw a stone of one-half or one pound weight farther than you could a thousandth part of it. For the impetus in that thousandth part is so small that it is overcome immediately by the resisting air.

2 From this theory also appears the cause of why the natural motion of a heavy body downward is continually accelerated (*continue velocitatur*). For from the beginning only the gravity was moving it. Therefore, it moved more slowly, but in moving it impressed in the heavy body an impetus. This impetus now [acting] together with its gravity moves it. Therefore, the motion becomes faster; and by the amount it is faster, so the impetus becomes more intense. Therefore, the movement evidently becomes continually faster.

[The impetus then also explains why] one who wishes to jump a long distance drops back a way in order to run faster, so that by running he might acquire an impetus which would carry him a longer distance in the jump. Whence the person so running and jumping does not feel the air moving him, but [rather] feels the air in front strongly resisting him.

Also, since the Bible does not state that appropriate intelligences move the celestial bodies, it could be said that it does not appear necessary to posit intelligences of this kind, because it would be answered that God, when He created the world, moved each of the celestial orbs as He pleased, and in moving them He impressed in them impetuses which moved them without his having to move them any more except by the method of general influence whereby he concurs as a co-agent in all things which take place; "for thus on the seventh day He rested from all work which He had executed by committing to others the actions and the passions in turn." And these impetuses which He impressed in the celestial bodies were not decreased nor corrupted afterwards, because there was no inclination of the celestial bodies for other movements. Nor was there resistance which would be corruptive or repressive of that impetus. But this I do not say assertively, but [rather tentatively] so that I might seek from the theological masters what they might teach me in these matters as to how these things take place. . . .

7 The first [conclusion] is that that impetus is not the very local motion in which the projectile is moved, because that impetus moves the projectile and the mover produces motion. Therefore, the impetus produces that motion, and the same thing cannot produce itself. Therefore, etc.

Also since every motion arises from a motor being present and existing simultaneously with that which is moved, if the impetus were the motion, it would be necessary to assign some other motor from which that motion would arise. And the principal difficulty would return. Hence there would be no gain in positing such an impetus. But others cavil when they say that the prior part of the motion which produces the projection produces another part of the motion which is related successively and that produces another part and so on up to the cessation of the whole movement. But this is not probable, because the "producing something" ought to exist when the something is made, but the prior part of the motion does not exist when the posterior part exists, as was elsewhere stated. Hence, neither does the prior exist when the posterior is made. This consequence is obvious from this reasoning. For it was said elsewhere that motion is nothing else than "the very being produced" (*ipsum fieri*) and the "very being corrupted" (*ipsum corumpi*). Hence motion does not result when it *has been* produced (*factus est*) but when it *is being* produced (*fit*).

8 The second conclusion is that that impetus is not a purely successive thing (*res*), because motion is just such a thing and the definition of motion [as a successive thing] is fitting to it, as was stated elsewhere. And now it has just been affirmed that that impetus is not the local motion.

Also, since a purely successive thing is continually corrupted and produced, it continually demands a producer. But there cannot be assigned a producer of that impetus which would continue to be simultaneous with it.

9 The third conclusion is that that impetus is a thing of permanent nature (*res nature permanentis*), distinct from the local motion in which the projectile is moved. This is evident from the two aforesaid conclusions and from the preceding [statements]. And it is probable (*verisimile*) that that impetus is a quality naturally present and predisposed for moving a body in which it is impressed, just as it is said that a quality impressed in iron by a magnet moves the iron to the magnet. And it also is probable that just as that quality (the impetus) is impressed in the moving body along with the motion by the motor; so with the motion it is remitted, corrupted, or impeded by resistance or a contrary inclination.

10 And in the same way that a luminant generating light generates light reflexively because of an obstacle, so that impetus because of an obstacle acts reflexively. It is true, however, that other causes aptly concur with that impetus for greater or longer reflection. For example, the ball which we bounce with the palm in falling to earth is reflected higher than a stone, although the stone falls more swiftly and more impetuously (*impetuosius*) to the earth. This is because many things are curvable or intracompressible by violence which are innately disposed to return swiftly and by themselves to their correct position or to the disposition natural to them. In thus returning, they can impetuously push or draw something conjunct to them, as is evident in the case of the bow (*arcus*). Hence in this way the ball thrown to the hard ground is compressed into itself by the impetus of its motion; and immediately after striking, it returns swiftly to its sphericity by elevating itself upwards. From this elevation it acquires to itself an impetus which moves it upward a long distance.

Also, it is this way with a cither cord which, put under strong tension and percussion, remains a long time in a certain vibration (*tremulatio*) from which its sound continues a notable time. And this takes place as follows: As a result of striking [the chord] swiftly, it is bent violently in one direction, and so it returns swiftly toward its normal straight position. But on account of the impetus, it crosses beyond the normal straight position in the contrary direction and then agaid returns. It does this many times. For a similar reason a bell (*campana*), after the ringer ceases to draw [the chord], is moved a long time, first in one direction, now in another. And it cannot be easily and quickly brought to rest.

This, then, is the exposition of the question. I would be delighted if someone would discover a more probable way of answering it. And this is the end.

1.18

The Possibility of a Rotating Earth

Nicole Oresme

Nicole Oresme (c.1325–1382) was a student of Jean Buridan and extended the work of his great teacher. Like Buridan, Oresme made important contributions to numerous fields, but his most influential work was in mathematics (where he took important steps toward analytic geometry) and what we would today call physics. In this selection from his *Book of Heaven and Earth*, Oresme anticipates Copernicus by undermining both physical and scriptural objections to the daily rotation of the earth. He stops short of endorsing diurnal rotation, but the door had been opened; two centuries later, Copernicus would walk through it.

[Aristotle's text]: There are others who hold that the earth is at the center of the world and that it revolves and moves in a circuit around the pole established for this purpose, as is written in Plato's book called *Timaeus*.

[Oresme's commentary]: This was the opinion of a philosopher named Heraclides Ponticus, who maintained that the earth moves circularly and that the heavens remain at rest. Here Aristotle does not refute these theories, possibly because they seemed to him of slight probability and were, moreover, sufficiently criticized in philosophical and astrological writings.

However, subject, of course, to correction, it seems to me that it is possible to embrace the argument and consider with favor the conclusions set forth in the above opinion that the earth rather than the heavens has a diurnal or daily rotation. At the outset, I wish to state that it is impossible to demonstrate from any experience at all that the contrary is true; second, that no argument is conclusive; and third, I shall demonstrate why this is so.

As to the first point, let us examine one experience: we can see with our eyes the rising and setting of the sun, the moon, and several stars,

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while other stars turn around the arctic pole. Such a thing is due only to the motion of the heavens, [. . .] and, therefore, the heavens move with daily motion. Another experience is this one: if the earth is so moved, it makes its complete course in a natural day with the result that we and the trees and the houses are moved very fast toward the east; thus, it should seem to us that the air and wind are always coming very strong from the east and that it should make a noise such as it makes against the arrow shot from a crossbow or an even louder one, but the contrary is evident from experience. The third argument is Ptolemy's – namely, that, if someone were in a boat moving rapidly toward the east and shot an arrow straight upward, it would not fall in the boat but far behind it toward the west. Likewise, if the earth moves so very fast turning from west to east and if someone threw a stone straight upward, it would not fall back to the place from which it was thrown, but far to the west; and the contrary appears to be the case.

It seems to me that what I shall say below about these experiences could apply to all other theories which might be brought forward in this connection. Therefore, I state, in the first place, that the whole corporeal machine or the entire mass of all the bodies in the universe is divided into two parts: one is the heavens with the sphere of fire and the higher region of the air, all this part, according to Aristotle in Book I of *Meteors*, moves in a circle or revolves each day. The other part of the universe is all the rest – that is, the middle and lower regions of the air, the water, the earth, and the mixed bodies – and, according to Aristotle, all this part is immobile and has no daily motion.

Now, I take as a fact that local motion can be perceived only if we can see that one body assumes a different position relative to another body. For example, if a man is in a boat *a*, which is moving very smoothly either at rapid or slow speed, and if this man sees nothing except another boat *b*, which moves precisely like boat *a*, the one in which he is standing, I maintain that to this man it will appear that neither boat is moving. If *a* rests while *b* moves, he will be aware that *b* is moving; if *a* moves and *b* rests, it will seem to the man in *a* that *a* is resting and *b* is moving, just as before. Thus, if *a* rested an hour and *b* moved, and during the next hour it happened conversely that *a* moved and *b* rested, this man would not be able to sense this change or variation; it would seem to him that all this time *b* was moving. This fact is evident from experience, and the reason is that the two bodies *a* and *b* have a continual relationship to each other so that, when *a* moves, *b* rests and, conversely, when *b* moves, *a* rests. It is stated in Book Four of *The Perspective* by Witelo that we do not perceive motion unless we notice that one body is in the process of assuming a different position relative to another.

I say, therefore, that, if the higher of the two parts of the world mentioned above were moved today in daily motion – as it is – and the lower part remained motionless and if tomorrow the contrary were to happen so that the lower part moved in daily motion and the higher – that is, the heavens, etc. – remained at rest, we should not be able to sense or perceive this change, and everything would appear exactly the same both today and tomorrow with respect to this mutation. We should keep right on assuming that the part where we are was at rest while the other part was moving continually, exactly as it seems to a man in a moving boat that the trees on shore move. In the same way, if a man in the heavens, moved and carried along by their daily motion, could see the earth distinctly and its mountains, valleys, rivers, cities, and castles, it would appear to him that the earth was moving in daily motion, just as to us on earth it seems as though the heavens are moving. Likewise, if the earth moved with daily motion and the heavens were motionless, it would seem to us that the earth was immobile and that the heavens appeared to move; and this can be easily imagined by anyone with clear understanding. This obviously answers the first experience, for we could say that the sun and stars appear to rise and set as they do and that the heavens seem to revolve on account of the motion of the earth in which we live together with the elements.

To the second experience, the reply seems to be that, according to this opinion, not only the earth moves, but also with it the water and the air, as we stated above, although the water and air here below may be moved in addition by the winds or other forces. In a similar manner, if the air were closed in on a moving boat, it would seem to a person in that air that it was not moving.

Concerning the third experience which seems more complicated and which deals with the case of an arrow or stone thrown up into the air, etc., one might say that the arrow shot upward is moved toward the east very rapidly with the air through which it passes, along with all the lower portion of the world which we have already defined and which moves with daily motion; for this reason the arrow falls back to the place from which it was shot into the air. Such a thing could be possible in this way for, if a man were in a ship moving rapidly eastward without his being aware of the movement and if he drew his hand in a straight line down along the ship's mast, it would seem to him that his hand were moving with a rectilinear motion; so, according to this theory it seems to us that the same thing happens with the arrow which is shot straight down or straight up. Inside the boat moved rapidly eastward, there can be all kinds of movements – horizontal, criss-cross, upward, downward, in all directions – and they seem to be exactly the same as those when the ship is at rest. Thus, if a man in this boat walked toward the west less rapidly than the boat was moving toward the east, it would seem to the man that he was approaching the west when actually he was going east; and similarly as in the preceding case, all the motions here below would seem to be the same as though the earth rested.

Now, in order to explain the reply to the third experience in which this artificial illustration was used, I should like to present an example taken from nature, which, according to Aristotle, is true.

He supposes that there is a portion of pure fire called *a* in the higher region of the air; this fire, being very light, rises as high as possible to a place called *b* near the concave surface of the heavens [see Fig. 4]. I maintain that, just as with the arrow above, the motion of *a* in this case also must be compounded of rectilinear and, in part, of circular motion, because the region of the air and the sphere of fire through which *a* passed have, in Aristotle's opinion, circular motion. If they were not thus moved, *a* would go straight upward along the line *ab*; but because *b* is meanwhile drawn toward *c* by circular and daily motion, it appears that *a* describes the line *ac* as it ascends and that, therefore, the movement of *a* is compounded of rectilinear and of circular motion, and the movement of the arrow would be of this

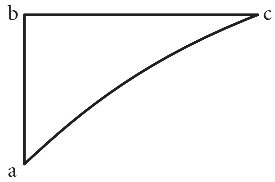

Figure 4 Path of *a*, *b* and *c* (Oresme, "The Compatibility of the Earth's Diurnal Rotation" from Edward Grant, *A Source Book in Medieval Science* [Cambridge: Harvard University Press, 1974], p. 67)

kind of mixed or compound motion that we spoke of in Chapter Three of Book I. I conclude, then, that it is impossible to demonstrate by any experience that the heavens have daily motion and that the earth does not have the same.

[. . .]

. . . If neither experience not reason indicates the contrary, it is much more reasonable, as stated above, that all the principal movements of the simple bodies in the world should go or proceed in one direction or manner. Now, according to the philosophers and astronomers, it cannot be that all bodies move from east to west; but, if the earth moves as we have indicated, then all proceed alike from west to east – that is, the earth by rotating once around the poles from west to east in one natural day and the heavenly bodies around the zodiacal poles: the moon in one month, the sun in one year, Mars in approximately two years, and so on with the other bodies. It is unnecessary to posit in the heavens other primary poles or two kinds of motion, one from the east to the west and the other on different poles in the opposite direction, but such an assumption is definitely necessary if the heavens move with diurnal motion. . . .

. . . [I]f we assume that the earth moves as stated above, . . . appearances can be saved in this way, as is evident from the reply to the seventh argument, presented against this opinion. . . . Thus, it is apparent that one cannot demonstrate by any experience whatever that the heavens move with diurnal motion; whatever the fact may be, assuming that the heavens move and the earth does not or that the earth moves and the heavens do not, to an eye in the heavens which could see the earth clearly, it would appear to move; if the eye were on the earth, the heavens would appear to move. Nor would the vision of this eye be deceived, for it can sense or see nothing but the process of the movement itself. But if the motion is relative to some particular body or object, this judgment is made by the senses from within that particular body, as Witelo explains in *The Perspective*; and the senses are often deceived in such cases, as was related above in the example of the man on the moving ship. Afterward, it was demonstrated how it cannot be proved conclusively by argument that the heavens move. In the third place, we offered arguments opposing their diurnal motion. However, everyone maintains, and I think myself, that the heavens do move and not the earth: For God hath established the world which shall not be moved, in spite of contrary reasons because they are clearly not conclusive persuasions. However, after considering all that has been said, one could then believe that the earth moves and not the heavens, for the opposite is not clearly evident. Nevertheless, at first sight, this seems as much against natural reason as, or more against natural reason than, all or many of the articles of our faith. What I have said by way of diversion or intellectual exercise can in this manner serve as a valuable means of refuting and checking those who would like to impugn our faith by argument.