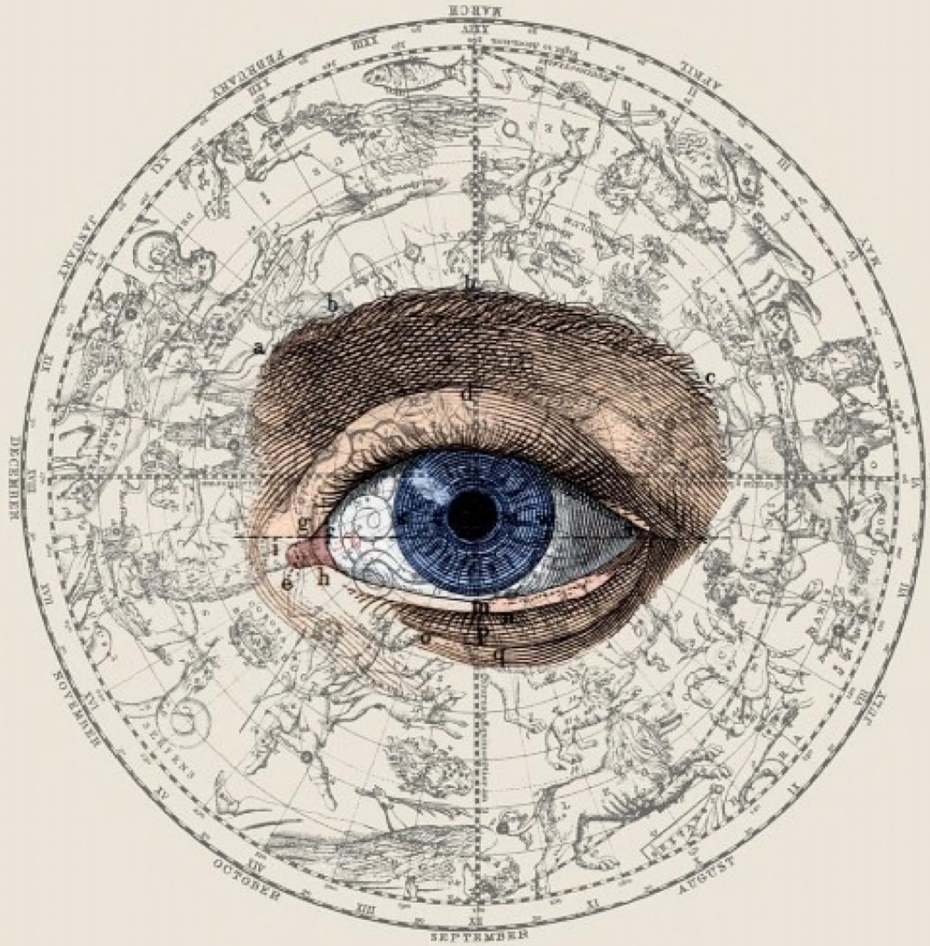
TO EXPLAIN THE WORLD

THE DISCOVERY OF MODERN SCIENCE



STEVEN WEINBERG

WINNER OF THE NOBEL PRIZE

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ABOUT THE AUTHOR

Steven Weinberg has won the Nobel Prize in Physics, the National Medal of Science, the Lewis Thomas Prize for the Scientist as Poet and numerous honorary degrees. He is a member of the National Academy of Science, the Royal Society of London and the American Philosophical Society. A long-time contributor to the *New York Review of Books,* he is the author of *The First Three Minutes* and *Dreams of a Final Theory,* among other books.

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TO EXPLAIN THE WORLD

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‘Weinberg advances keen insights … into the intellectual structure of science … A compelling reminder of how science works – and why it matters’ *Booklist*

‘With his usual scholarly aplomb, Weinberg leads readers on a tour of early scientific theory, from the ancient Greeks to the Scientific Revolution of the seventeenth century … Accessible and smoothly written, Weinberg’s book offers new insights on what has become familiar territory for pop-science readers’ *Publishers Weekly*

‘Entertaining … The book should make any history of science buff’s reading list … Weinberg gets it right’ *Forbes*

To Louise, Elizabeth, and Gabrielle

These three hours that we have spent,
Walking here, two shadows went
Along with us, which we ourselves produced;
But, now the sun is just above our head,
We do those shadows tread;
And to brave clearness all things are reduced.

John Donne, “A Lecture upon the Shadow”

Preface

I am a physicist, not a historian, but over the years I have become increasingly fascinated by the history of science. It is an extraordinary story, one of the most interesting in human history. It is also a story in which scientists like myself have a personal stake. Today's research can be aided and illuminated by a knowledge of its past, and for some scientists knowledge of the history of science helps to motivate present work. We hope that our research may turn out to be a part, however small, of the grand historical tradition of natural science.

Where my own past writing has touched on history, it has been mostly the modern history of physics and astronomy, roughly from the late nineteenth century to the present. Although in this era we have learned many new things, the goals and standards of physical science have not materially changed. If physicists of 1900 were somehow taught today's Standard Model of cosmology or of elementary particle physics, they would have found much to amaze them, but the idea of seeking mathematically formulated and experimentally validated impersonal principles that explain a wide variety of phenomena would have seemed quite familiar.

A while ago I decided that I needed to dig deeper, to learn more about an earlier era in the history of science, when the goals and standards of science had not yet taken their present shape. As is natural for an academic, when I want to learn about something, I volunteer to teach a course on the subject. Over the past decade at the University of Texas, I have from time to time taught undergraduate courses on the history of physics and astronomy to students who had no special background in science, mathematics, or history. This book grew out of the lecture notes for those courses.

But as the book has developed, perhaps I have been able to offer something that goes a little beyond a simple narrative: it is the perspective of a modern working scientist on the science of the past. I have taken this opportunity to explain my views about the nature of physical science, and about its continued tangled relations with religion, technology, philosophy, mathematics, and aesthetics.

Before history there was science, of a sort. At any moment nature presents us with a variety of puzzling phenomena: fire, thunderstorms, plagues, planetary motion, light, tides, and so on. Observation of the world led to useful generalizations: fires are hot; thunder presages rain; tides are highest when the Moon is full or new, and so on. These became part of the common sense of mankind. But here and there, some people wanted more than just a collection of facts. They wanted to explain the world.

It was not easy. It is not only that our predecessors did not know what we know about the world—more important, they did not have anything like our ideas of what there was to know about the world, and how to learn it. Again and again in preparing the lectures for my course I have been impressed with how different the work of science in past centuries was from the science of my own times. As the much quoted lines of a novel of L. P. Hartley put it, “The past is a foreign country; they do things differently there.” I hope that in this book I have been able to give the reader not only an idea of what happened in the history of the exact sciences, but also a sense of how hard it has all been.

So this book is not solely about how we came to learn various things about the world. That is naturally a concern of any history of science. My focus in this book is a little different—it is how we came to learn how to learn about the world.

I am not unaware that the word “explain” in the title of this book raises problems for philosophers of science. They have pointed out the difficulty in drawing a precise distinction between explanation and description. (I will have a little to say about this in Chapter 8.) But this is a work on the history rather than the philosophy of science. By explanation I mean something admittedly imprecise, the same as is meant in ordinary life when we try to explain why a horse has won a race or why an airplane has crashed.

The word “discovery” in the subtitle is also problematic. I had thought of using *The Invention of Modern Science* as a subtitle. After all, science could hardly exist without human beings to practice it. I chose “Discovery” instead of “Invention” to suggest that science is the way it is not so much because of various adventitious historic acts of invention, but because of the way nature is. With all its imperfections, modern science is a technique that is sufficiently well tuned to nature so that it works—it is a practice that allows us to learn reliable things about the world. In this sense, it is a technique that was waiting for people to discover it.

Thus one can talk about the discovery of science in the way that a historian can talk about the discovery of agriculture. With all its variety and imperfections, agriculture is the way it is because its practices are sufficiently well tuned to the realities of biology so that it works—it allows us to grow food.

I also wanted with this subtitle to distance myself from the few remaining social constructivists: those sociologists, philosophers, and historians who try to explain not only the process but even the results of science as products of a particular cultural milieu.

Among the branches of science, this book will emphasize physics and astronomy. It was in physics, especially as applied to astronomy, that science first took a modern form. Of course there are limits to the extent to which sciences like biology, whose principles depend so much on historical accidents, can or should be modeled on physics. Nevertheless, there is a sense in which the development of scientific biology as well as chemistry in the nineteenth and twentieth centuries followed the model of the revolution in physics of the seventeenth century.

Science is now international, perhaps the most international aspect of our civilization, but the discovery of modern science happened in what may loosely be called the West. Modern science learned its methods from research done in Europe during the scientific revolution, which in turn evolved from work done in Europe and in Arab countries during the Middle Ages, and ultimately from the precocious science of the Greeks. The West borrowed much scientific knowledge from elsewhere—geometry from Egypt, astronomical data from Babylon, the techniques of arithmetic from Babylon and India, the magnetic compass from China, and so on—but as far as I know, it did not import the *methods* of modern science. So this book will emphasize the West (including medieval Islam) in just the way that was deplored by Oswald Spengler and Arnold Toynbee: I will have little to say about science outside the West, and nothing at all to say about the interesting but entirely isolated progress made in pre-Columbian America.

In telling this story, I will be coming close to the dangerous ground that is most carefully avoided by contemporary historians, of judging the past by the standards of the present. This is an irreverent history; I am not unwilling to criticize the methods and theories of the past from a modern viewpoint. I have even taken some pleasure in uncovering a few errors made by scientific heroes that I have not seen mentioned by historians.

A historian who devotes years to study the works of some great man of the past may come to exaggerate what his hero has accomplished. I have seen this in particular in works on Plato, Aristotle, Avicenna, Grosseteste, and Descartes. But it is not my purpose here to accuse some past natural philosophers of stupidity. Rather, by showing how far these very intelligent individuals were from our present conception of science, I want to show how difficult was the discovery of modern science, how far from obvious are its practices and standards. This also serves as a warning, that science may not yet be in its final form. At several points in this book I suggest that, as great as is the progress that has been made in the methods of science, we may today be repeating some of the errors of the past.

Some historians of science make a shibboleth of not referring to present scientific knowledge in studying the science of the past. I will instead make a point of using present knowledge to clarify past science. For instance, though it might be an interesting intellectual exercise to try to understand how the Hellenistic astronomers Apollonius and Hipparchus developed the theory that the planets go around the Earth on looping epicyclic orbits by using only the data that had been available to them, this is impossible, for much of the data they used is lost. But we do know that in ancient times the Earth and planets went around the Sun on nearly circular orbits, just as they do today, and by using this knowledge we will be able to understand how the data available to ancient astronomers could have suggested to them their theory of epicycles. In any case, how can anyone today, reading about ancient astronomy, forget our present knowledge of what actually goes around what in the solar system?

For readers who want to understand in greater detail how the work of past scientists fits in with what actually exists in nature, there are "technical notes" at the back of the book. It is not necessary to read these notes to follow the book's main text, but some readers may learn a few odd bits of physics and astronomy from them, as I did in preparing them.

Science is not now what it was at its start. Its results are impersonal. Inspiration and aesthetic judgment are important in the development of scientific theories, but the verification of these theories relies finally on impartial experimental tests of their predictions. Though mathematics is used in the formulation of physical theories and in working out their consequences, science is not a branch of mathematics, and scientific theories cannot be deduced by purely mathematical reasoning. Science and technology benefit each other, but at its most fundamental level science is not undertaken for any practical reason. Though science has nothing to say one way or the other about the existence of God or an afterlife, its goal is to find explanations of natural phenomena that are purely naturalistic. Science is cumulative; each new theory incorporates successful earlier theories as approximations, and even explains why these approximations work, when they do work.

None of this was obvious to the scientists of the ancient world or the Middle Ages, and all of it was learned only with great difficulty in the scientific revolution of the sixteenth and seventeenth centuries. Nothing like modern science was a goal from the beginning. How then did we get to the scientific revolution, and beyond it to where we are now? That is what we must try to learn as we explore the discovery of modern science.

Part I

GREEK PHYSICS

During or before the flowering of Greek science, significant contributions to technology, mathematics, and astronomy were being made by the Babylonians, Chinese, Egyptians, Indians, and other peoples. Nevertheless, it was from Greece that Europe drew its model and its inspiration, and it was in Europe that modern science began, so the Greeks played a special role in the discovery of science.

One can argue endlessly about why it was the Greeks who accomplished so much. It may be significant that Greek science began when Greeks lived in small independent city-states, many of them democracies. But as we shall see, the Greeks made their most impressive scientific achievements after these small states had been absorbed into great powers: the Hellenistic kingdoms, and then the Roman Empire. The Greeks in Hellenistic and Roman times made contributions to science and mathematics that were not significantly surpassed until the scientific revolution of the sixteenth and seventeenth centuries in Europe.

This part of my account of Greek science deals with physics, leaving Greek astronomy to be discussed in Part II. I have divided Part I into five chapters, dealing in more or less chronological order with five modes of thought with which science has had to come to terms: poetry, mathematics, philosophy, technology, and religion. The theme of the relationship of science to these five intellectual neighbors will recur throughout this book.

1

Matter and Poetry

First, to set the scene. By the sixth century BC the western coast of what is now Turkey had for some time been settled by Greeks, chiefly speaking the Ionian dialect. The richest and most powerful of the Ionian cities was Miletus, founded at a natural harbor near where the river Meander flows into the Aegean Sea. In Miletus, over a century before the time of Socrates, Greeks began to speculate about the fundamental substance of which the world is made.

I first learned about the Milesians as an undergraduate at Cornell, taking courses on the history and philosophy of science. In lectures I heard the Milesians called "physicists." At the same time, I was also attending classes on physics, including the modern atomic theory of matter. There seemed to me to be very little in common between Milesian and modern physics. It was not so much that the Milesians were wrong about the nature of matter, but rather that I could not understand how they could have reached their conclusions. The historical record concerning Greek thought before the time of Plato is fragmentary, but I was pretty sure that during the Archaic and Classical eras (roughly from 600 to 450 BC and from 450 to 300 BC, respectively) neither the Milesians nor any of the other Greek students of nature were reasoning in anything like the way scientists reason today.

The first Milesian of whom anything is known was Thales, who lived about two centuries before the time of Plato. He was supposed to have predicted a solar eclipse, one that we know did occur in 585 BC and was visible from Miletus. Even with the benefit of Babylonian eclipse records it's unlikely that Thales could have made this prediction, because any solar eclipse is visible from only a limited geographic region, but the fact that Thales was credited with this prediction shows that he probably flourished in the early 500s BC. We don't know if Thales put any of his ideas into writing. In any case, nothing written by Thales has survived, even as a quotation by later authors. He is a legendary figure, one of those (like his contemporary Solon, who was supposed to have founded the Athenian constitution) who were conventionally listed in Plato's time as the "seven sages" of Greece. For instance, Thales was reputed to have proved or brought from Egypt a famous theorem of geometry (see Technical Note 1). What matters to us here is that Thales was said to hold the view that all matter is composed of a single fundamental substance. According to Aristotle's *Metaphysics*, "Of the first philosophers, most thought the principles which were of the nature of matter were the only principles of all things.... Thales, the founder of this school of philosophy, says the principle is water."[1] Much later, Diogenes Laertius (fl. AD 230), a biographer of the Greek philosophers, wrote, "His doctrine was that water is the universal primary substance, and that the world is animate and full of divinities."[2]

By "universal primary substance" did Thales mean that all matter is composed of water? If so, we have no way of telling how he came to this conclusion, but if someone is convinced that all matter is composed of a single common substance, then water is not a bad candidate. Water not only occurs as a liquid but can be easily converted into a solid by freezing or into a vapor by boiling. Water evidently also is essential to life. But we don't know if Thales thought that rocks, for example, are really formed from ordinary water, or only that there is something profound that rock and all other solids have in common with frozen water.

Thales had a pupil or associate, Anaximander, who came to a different conclusion. He too thought that there is a single fundamental substance, but he did not associate it with any common material. Rather, he identified it as a mysterious substance he called the unlimited, or infinite. On this, we have a description of his views by Simplicius, a Neoplatonist who lived about a thousand years later. Simplicius includes what seems to be a direct quotation from Anaximander, indicated here in italics:

> Of those who say that [the principle] is one and in motion and unlimited, Anaximander, son of Praxiades, a Milesian who became successor and pupil to Thales, said that the unlimited is both principle and element of the things that exist. He says that it is neither water nor any other of the so-called elements, but some other unlimited nature, from which the heavens and the worlds in them come about; and the things from which is the coming into being for the things that exist are also those into which their destruction comes about, in accordance with what must be. *For they give justice and reparation to one another for their offence in accordance with the ordinance of time*—speaking of them thus in rather poetical terms. And it is clear that, having observed the change of the four elements into one another, he did not think fit to make any one of these an underlying stuff, but something else apart from these.[3]

A little later another Milesian, Anaximenes, returned to the idea that everything is made of some one common substance, but for Anaximenes it was not water but air. He wrote one book, of which just one whole sentence has survived: "The soul, being our air, controls us, and breath and air encompass the whole world."[4]

With Anaximenes the contributions of the Milesians came to an end. Miletus and the other Ionian cities of Asia Minor became subject to the growing Persian Empire in about 550 BC. Miletus started a revolt in 499 BC and was devastated by the Persians. It revived later as an important Greek city, but it never again became a center of Greek science.

Concern with the nature of matter continued outside Miletus among the Ionian Greeks. There is a hint that earth was nominated as the fundamental substance by Xenophanes, who was born around 570 BC at Colophon in Ionia and migrated to southern Italy. In one of his poems, there is the line "For all things come from earth, and in earth all things end."[5] But perhaps this was just his version of the familiar funerary sentiment, "Ashes to ashes, dust to dust." We will meet Xenophanes again in another connection, when we come to religion in Chapter 5.

At Ephesus, not far from Miletus, around 500 BC Heraclitus taught that the fundamental substance is fire. He wrote a book, of which only fragments survive. One of these fragments tells us, "This ordered *kosmos*,* which is the same for all, was not created by any one of the gods or of mankind, but it was ever and is and shall be ever-living Fire, kindled in measure and quenched in measure."[6] Heraclitus elsewhere emphasized the endless changes in nature, so for him it was more natural to take flickering fire, an agent of change, as the fundamental element than the more stable earth, air, or water.

The classic view that all matter is composed not of one but of four elements—water, air, earth, and fire—is probably due to Empedocles. He lived in Acragas, in Sicily (the modern Agrigento), in the mid-400s BC, and he is the first and nearly the only Greek in this early part of the story to have been of Dorian rather than of Ionian stock. He wrote two hexameter poems, of which many fragments have survived. In *On Nature*, we find "how from the mixture of Water, Earth, Aether, and Sun [fire] there came into being the forms and colours of mortal things"[7] and also "fire and water and earth and the endless height of air, and cursed Strife apart from them, balanced in every way, and Love among them, equal in height and breadth."[8]

It is possible that Empedocles and Anaximander used terms like "love" and "strife" or "justice" and "injustice" only as metaphors for order and disorder, in something like the way Einstein occasionally used "God" as a metaphor for the unknown fundamental laws of nature. But we should not force a modern interpretation onto the pre-Socratics' words. As I see it, the intrusion of human emotions like Empedocles' love and strife, or of values like Anaximander's justice and reparation, into speculations about the nature of matter is more likely to be a sign of the great distance of the thought of the pre-Socratics from the spirit of modern physics.

These pre-Socratics, from Thales to Empedocles, seem to have thought of the elements as smooth undifferentiated substances. A different view that is closer to modern understanding was introduced a little later at Abdera, a town on the seacoast of

Thrace founded by refugees from the revolt of the Ionian cities against Persia started in 499 BC. The first known Abderite philosopher is Leucippus, from whom just one sentence survives, suggesting a deterministic worldview: "No thing happens in vain, but everything for a reason and by necessity."[9] Much more is known of Leucippus' successor Democritus. He was born at Miletus, and had traveled in Babylon, Egypt, and Athens before settling in Abdera in the late 400s BC. Democritus wrote books on ethics, natural science, mathematics, and music, of which many fragments survive. One of these fragments expresses the view that all matter consists of tiny indivisible particles called atoms (from the Greek for "uncuttable"), moving in empty space: "Sweet exists by convention, bitter by convention; atoms and Void [alone] exist in reality."[10]

Like modern scientists, these early Greeks were willing to look beneath the surface appearance of the world, pursuing knowledge about a deeper level of reality. The matter of the world does not appear at first glance as if it is all made of water, or air, or earth, or fire, or all four together, or even of atoms.

Acceptance of the esoteric was taken to an extreme by Parmenides of Elea (the modern Velia) in southern Italy, who was greatly admired by Plato. In the early 400s BC Parmenides taught, contra Heraclitus, that the apparent change and variety in nature are an illusion. His ideas were defended by his pupil Zeno of Elea (not to be confused with other Zenos, such as Zeno the Stoic). In his book *Attacks*, Zeno offered a number of paradoxes to show the impossibility of motion. For instance, to traverse the whole course of a racetrack, it is necessary first to cover half the distance, and then half the remaining distance, and so on indefinitely, so that it is impossible ever to traverse the whole track. By the same reasoning, as far as we can tell from surviving fragments, it appeared to Zeno to be impossible ever to travel *any* given distance, so that all motion is impossible.

Of course, Zeno's reasoning was wrong. As pointed out later by Aristotle,[11] there is no reason why we cannot accomplish an infinite number of steps in a finite time, as long as the time needed for each successive step decreases sufficiently rapidly. It is true that an infinite series like $\frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \ldots$ has an infinite sum, but the infinite series $\frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \ldots$ has a finite sum, in this case equal to 1.

What is most striking is not so much that Parmenides and Zeno were wrong as that they did not bother to explain why, if motion is impossible, things appear to move. Indeed, none of the early Greeks from Thales to Plato, in either Miletus or Abdera or Elea or Athens, ever took it on themselves to explain in detail how their theories about ultimate reality accounted for the appearances of things.

This was not just intellectual laziness. There was a strain of intellectual snobbery among the early Greeks that led them to regard an understanding of appearances as not worth having. This is just one example of an attitude that has blighted much of the history of science. At various times it has been thought that circular orbits are more perfect than elliptical orbits, that gold is more noble than lead, and that man is a higher being than his fellow simians.

Are we now making similar mistakes, passing up opportunities for scientific progress because we ignore phenomena that seem unworthy of our attention? One can't be sure, but I doubt it. Of course, we cannot explore everything, but we choose problems that we think, rightly or wrongly, offer the best prospect for scientific understanding. Biologists who are interested in chromosomes or nerve cells study animals like fruit flies and squid, not noble eagles and lions. Elementary particle physicists are sometimes accused of a snobbish and expensive preoccupation with phenomena at the highest attainable energies, but it is only at high energies that we can create and study hypothetical particles of high mass, like the dark matter particles that astronomers tell us make up five-sixths of the matter of the universe. In any case, we give plenty of attention to phenomena at low energies, like the intriguing mass of neutrinos, about a millionth the mass of the electron.

In commenting on the prejudices of the pre-Socratics, I don't mean to say that a priori reasoning has no place in science. Today, for instance, we expect to find that our deepest physical laws satisfy principles of symmetry, which state that physical laws do not change when we change our point of view in certain definite ways. Just like Parmenides' principle of changelessness, some of these symmetry principles are not immediately apparent in physical phenomena—they are said to be spontaneously broken. That is, the equations of our theories have certain simplicities, for instance treating certain species of particles in the same way, but these simplicities are not shared by the solutions of the equations, which govern actual phenomena. Nevertheless, unlike the commitment of Parmenides to changelessness, the a priori presumption in favor of principles of symmetry arose from many years of experience in searching for physical principles that describe the real world, and broken as well as unbroken symmetries are validated by experiments that confirm their consequences. They do not involve value judgments of the sort we apply to human affairs.

With Socrates, in the late fifth century BC, and Plato, some forty years later, the center of the stage for Greek intellectual life moved to Athens, one of the few cities of Ionian Greeks on the Greek mainland. Almost all of what we know about Socrates comes from his appearance in the dialogues of Plato, and as a comic character in Aristophanes' play *The Clouds.* Socrates does not seem to have put any of his ideas into writing, but as far as we can tell he was not very interested in natural science. In Plato's dialogue *Phaedo* Socrates recalls how he was disappointed in reading a book by Anaxagoras (about whom more in Chapter 7) because Anaxagoras described the Earth, Sun, Moon, and stars in purely physical terms, without regard to what is best.[12]

Plato, unlike his hero Socrates, was an Athenian aristocrat. He was the first Greek philosopher from whom many writings have survived pretty much intact. Plato, like Socrates, was more concerned with human affairs than with the nature of matter. He hoped for a political career that would allow him to put his utopian and antidemocratic ideas into practice. In 367 BC Plato accepted an invitation from Dionysius II to come to Syracuse and help reform its government, but, fortunately for Syracuse, nothing came of the reform project.

In one of his dialogues, the *Timaeus*, Plato brought together the idea of four elements with the Abderite notion of atoms. Plato supposed that the four elements of Empedocles consisted of particles shaped like four of the five solid bodies known in mathematics as regular polyhedrons: bodies with faces that are all identical polygons, with all edges identical, coming together at identical vertices. (See Technical Note 2.) For instance, one of the regular polyhedrons is the cube, whose faces are all identical squares, three squares meeting at each vertex. Plato took atoms of earth to have the shape of cubes. The other regular polyhedrons are the tetrahedron (a pyramid with four triangular faces), the eight-sided octahedron, the twenty-sided icosahedron, and the twelve-sided dodecahedron. Plato supposed that the atoms of fire, air, and water have the shapes respectively of the tetrahedron, octahedron, and icosahedron. This left the dodecahedron unaccounted for. Plato regarded it as representing the *kosmos.* Later Aristotle introduced a fifth element, the ether or quintessence, which he supposed filled the space above the orbit of the Moon.

It has been common in writing about these early speculations regarding the nature of matter to emphasize how they prefigure features of modern science. Democritus is particularly admired; one of the leading universities in modern Greece is named Democritus University. Indeed, the effort to identify the fundamental constituents of matter continued for millennia, though with changes from time to time in the menu of elements. By early modern times alchemists had identified three supposed elements: mercury, salt, and sulfur. The modern idea of chemical elements dates from the chemical revolution instigated by Priestley, Lavoisier, Dalton, and others at the end of the eighteenth century, and now incorporates 92 naturally occurring elements, from hydrogen to uranium (including mercury and sulfur but not salt) plus a growing list of artificially created elements heavier than uranium. Under normal conditions, a pure chemical element consists of atoms all of the same type, and the elements are distinguished from one another by the type of atom of which they are composed. Today we look beyond the chemical elements to the elementary particles of which atoms are composed, but one way or another we continue the search, begun at Miletus, for the fundamental constituents of nature.

Nevertheless, I think one should not overemphasize the modern aspects of Archaic or Classical Greek science. There is an important feature of modern science that is almost completely missing in all the thinkers I have mentioned, from Thales to Plato: none of them attempted to verify or even (aside perhaps from Zeno) seriously to justify their speculations. In reading their writings, one continually wants to ask, “How do you know?” This is just as true of Democritus as of the others. Nowhere in the fragments of his books that survive do we see any effort to show that matter really is composed of atoms.

Plato’s ideas about the five elements give a good example of his insouciant attitude toward justification. In *Timaeus*, he starts not with regular polyhedrons but with triangles, which he proposes to join together to form the faces of the polyhedrons. What sort of triangles? Plato proposes that these should be the isosceles right triangle, with angles 45°, 45°, and 90°; and the right triangle with angles 30°, 60°, and 90°. The square faces of the cubic atoms of earth can be formed from two isosceles right triangles, and the triangular faces of the tetrahedral, octahedral, and icosahedral atoms of fire, air, and water (respectively) can each be formed from two of the other right triangles. (The dodecahedron, which mysteriously represents the cosmos, cannot be constructed in this way.) To explain this choice, Plato in *Timaeus* says, “If anyone can tell us of a better choice of triangle for the construction of the four bodies, his criticism will be welcome; but for our part we propose to pass over all the rest.… It would be too long a story to give the reason, but if anyone can produce a proof that it is not so we will welcome his achievement.”[13] I can imagine the reaction today if I supported a new conjecture about matter in a physics article by saying that it would take too long to explain my reasoning, and challenging my colleagues to prove the conjecture is not true.

Aristotle called the earlier Greek philosophers *physiologi,* and this is sometimes translated as “physicists,”[14] but that is misleading. The word *physiologi* simply means students of nature (*physis*), and the early Greeks had very little in common with today's physicists. Their theories had no bite. Empedocles could speculate about the elements, and Democritus about atoms, but their speculations led to no new information about nature—and certainly to nothing that would allow their theories to be tested.

It seems to me that to understand these early Greeks, it is better to think of them not as physicists or scientists or even philosophers, but as poets.

I should be clear about what I mean by this. There is a narrow sense of poetry, as language that uses verbal devices like meter, rhyme, or alliteration. Even in this narrow sense, Xenophanes, Parmenides, and Empedocles all wrote in poetry. After the Dorian invasions and the breakup of the Bronze Age Mycenaean civilization in the twelfth century BC, the Greeks had become largely illiterate. Without writing, poetry is almost the only way that people can communicate to later generations, because poetry can be remembered in a way that prose cannot. Literacy revived among the Greeks sometime around 700 BC, but the new alphabet borrowed from the Phoenicians was first used by Homer and Hesiod to write poetry, some of it the long-remembered poetry of the Greek dark ages. Prose came later.

Even the early Greek philosophers who wrote in prose, like Anaximander, Heraclitus, and Democritus, adopted a poetic style. Cicero said of Democritus that he was more poetic than many poets. Plato when young had wanted to be a poet, and though he wrote prose and was hostile to poetry in the *Republic*, his literary style has always been widely admired.

I have in mind here poetry in a broader sense: language chosen for aesthetic effect, rather than in an attempt to say clearly what one actually believes to be true. When Dylan Thomas writes, "The force that through the green fuse drives the flower drives my green age," we do not regard this as a serious statement about the unification of the forces of botany and zoology, and we do not seek verification; we (or at least I) take it rather as an expression of sadness about age and death.

At times it seems clear that Plato did not intend to be taken literally. One example mentioned above is his extraordinarily weak argument for the choice he made of two triangles as the basis of all matter. As an even clearer example, in the *Timaeus* Plato introduced the story of Atlantis, which supposedly flourished thousands of years before his own time. Plato could not possibly have seriously thought that he really knew anything about what had happened thousands of years earlier.

I don't at all mean to say that the early Greeks decided to write poetically in order to avoid the need to validate their theories. They felt no such need. Today we test our speculations about nature by using proposed theories to draw more or less precise conclusions that can be tested by observation. This did not occur to the early Greeks, or to many of their successors, for a very simple reason: *they had never seen it done.*

There are signs here and there that even when they did want to be taken seriously, the early Greeks had doubts about their own theories, that they felt reliable knowledge was unattainable. I used one example in my 1972 treatise on general relativity. At the head of a chapter about cosmological speculation, I quoted some lines of Xenophanes: "And as for certain truth, no man has seen it, nor will there ever be a man who knows about the gods and about the things I mention. For if he succeeds to the full in saying what is completely true, he himself is nevertheless unaware of it, and opinion is fixed by fate upon all things."[15] In the same vein, in *On the Forms*, Democritus remarked, "We in reality know nothing firmly" and "That in reality we do not know how each thing is or is not has been shown in many ways."[16]

There remains a poetic element in modern physics. We do not write in poetry; much of the writing of physicists barely reaches the level of prose. But we seek beauty in our theories, and use aesthetic judgments as a guide in our research. Some of us think that this works because we have been trained by centuries of success and failure in physics research to anticipate certain aspects of the laws of nature, and through this experience we have come to feel that these features of nature's laws are beautiful.[17] But we do not take the beauty of a theory as convincing evidence of its truth.

For example, string theory, which describes the different species of elementary particles as various modes of vibration of tiny strings, is very beautiful. It appears to be just barely consistent mathematically, so that its structure is not arbitrary, but largely fixed by the requirement of mathematical consistency. Thus it has the beauty of a rigid art form—a sonnet or a sonata. Unfortunately, string theory has not yet led to any predictions that can be tested experimentally, and as a result theorists (at least most of us) are keeping an open mind as to whether the theory actually applies to the real world. It is this insistence on verification that we most miss in all the poetic students of nature, from Thales to Plato.

It was in pure mathematics rather than in physics that the Pythagoreans made the greatest progress. Everyone has heard of *the* Pythagorean theorem, that the area of a square whose edge is the hypotenuse of a right triangle equals the sum of the areas of the two squares whose edges are the other two sides of the triangle. No one knows which if any of the Pythagoreans proved this theorem, or how. It is possible to give a simple proof based on a theory of proportions, a theory due to the Pythagorean Archytas of Tarentum, a contemporary of Plato. (See Technical Note 4. The proof given as Proposition 46 of Book I of Euclid's *Elements* is more complicated.) Archytas also solved the famous problem of constructing a cube of twice the volume of a given cube, though not by solely geometric means.

The Pythagorean theorem led directly to another great discovery: geometric constructions can involve lengths that cannot be expressed as ratios of whole numbers. If the two sides of a right triangle adjacent to the right angle each have a length (in some units of measurement) equal to 1, then the total area of the two squares with these edges is $1^2 + 1^2 = 2$, so according to the Pythagorean theorem the length of the hypotenuse must be a number whose square is 2. But it is easy to show that a number whose square is 2 cannot be expressed as a ratio of whole numbers. (See Technical Note 5.) The proof is given in Book X of Euclid's *Elements,* and mentioned earlier by Aristotle in his *Prior Analytics*[4] as an example of a *reductio ad impossibile,* but without giving the original source. There is a legend that this discovery is due to the Pythagorean Hippasus, possibly of Metapontum in southern Italy, and that he was exiled or murdered by the Pythagoreans for revealing it.

We might today describe this as the discovery that numbers like the square root of 2 are irrational—they cannot be expressed as ratios of whole numbers. According to Plato,[5] it was shown by Theodorus of Cyrene that the square roots of 3, 5, 6, . . ., 15, 17, etc. (that is, though Plato does not say so, the square roots of all the whole numbers other than the numbers 1, 4, 9, 16, etc., that are the squares of whole numbers) are irrational in the same sense. But the early Greeks would not have expressed it this way.

Rather, as the translation of Plato has it, the sides of squares whose areas are 2, 3, 5, etc., square feet are “incommensurate” with a single foot. The early Greeks had no conception of any but rational numbers, so for them quantities like the square root of 2 could be given only a geometric significance, and this constraint further impeded the development of arithmetic.

The tradition of concern with pure mathematics was continued in Plato’s Academy. Supposedly there was a sign over its entrance, saying that no one should enter who was ignorant of geometry. Plato himself was no mathematician, but he was enthusiastic about mathematics, perhaps in part because, during the journey to Sicily to tutor Dionysius the Younger of Syracuse, he had met the Pythagorean Archytas.

One of the mathematicians at the Academy who had a great influence on Plato was Theaetetus of Athens, who was the title character of one of Plato’s dialogues and the subject of another. Theaetetus is credited with the discovery of the five regular solids that, as we have seen, provided a basis for Plato’s theory of the elements. The proof* offered in Euclid’s *Elements* that these are the only possible convex regular solids may be due to Theaetetus, and Theaetetus also contributed to the theory of what are today called irrational numbers.

The greatest Hellenic mathematician of the fourth century BC was probably Eudoxus of Cnidus, a pupil of Archytas and a contemporary of Plato. Though resident much of his life in the city of Cnidus on the coast of Asia Minor, Eudoxus was a student at Plato’s Academy, and returned later to teach there. No writings of Eudoxus survive, but he is credited with solving a great number of difficult mathematical problems, such as showing that the volume of a cone is one-third the volume of the cylinder with the same base and height. (I have no idea how Eudoxus could have done this without calculus.) But his greatest contribution to mathematics was the introduction of a rigorous style, in which theorems are deduced from clearly stated axioms. It is this style that we find later in the writings of Euclid. Indeed, many of the details in Euclid’s *Elements* have been attributed to Eudoxus.

Though a great intellectual achievement in itself, the development of mathematics by Eudoxus and the Pythagoreans was a mixed blessing for natural science. For one thing, the deductive style of mathematical writing, enshrined in Euclid's *Elements*, was endlessly imitated by workers in natural science, where it is not so appropriate. As we will see, Aristotle's writing on natural science involves little mathematics, but at times it sounds like a parody of mathematical reasoning, as in his discussion of motion in *Physics*: "A, then, will move through B in a time C, and through D, which is thinner, in time E (if the length of B is equal to D), in proportion to the density of the hindering body. For let B be water and D be air."[6] Perhaps the greatest work of Greek physics is *On Floating Bodies* by Archimedes, to be discussed in Chapter 4. This book is written like a mathematics text, with unquestioned postulates followed by deduced propositions. Archimedes was smart enough to choose the right postulates, but scientific research is more honestly reported as a tangle of deduction, induction, and guesswork.

More important than the question of style, though related to it, is a false goal inspired by mathematics: to reach certain truth by the unaided intellect. In his discussion of the education of philosopher kings in the *Republic*, Plato has Socrates argue that astronomy should be done in the same way as geometry. According to Socrates, looking at the sky may be helpful as a spur to the intellect, in the same way that looking at a geometric diagram may be helpful in mathematics, but in both cases real knowledge comes solely through thought. Socrates explains in the *Republic* that "we should use the heavenly bodies merely as illustrations to help us study the other realm, as we would if we were faced with exceptional geometric figures."[7]

Mathematics is the means by which we deduce the consequences of physical principles. More than that, it is the indispensable language in which the principles of physical science are expressed. It often inspires new ideas about the natural sciences, and in turn the needs of science often drive developments in mathematics. The work of a theoretical physicist, Edward Witten, has provided so much insight into mathematics that in 1990 he was awarded one of the highest awards in mathematics, the Fields Medal. But mathematics is not a natural science. Mathematics in itself, without observation, cannot tell us anything about the world. And mathematical theorems can be neither verified nor refuted by observation of the world.

This was not clear in the ancient world, nor indeed even in early modern times. We have seen that Plato and the Pythagoreans considered mathematical objects such as numbers or triangles to be the fundamental constituents of nature, and we shall see that some philosophers regarded mathematical astronomy as a branch of mathematics, not of natural science.

The distinction between mathematics and science is pretty well settled. It remains mysterious to us why mathematics that is invented for reasons having nothing to do with nature often turns out to be useful in physical theories. In a famous article,[8] the physicist Eugene Wigner has written of "the unreasonable effectiveness of mathematics." But we generally have no trouble in distinguishing the ideas of mathematics from principles of science, principles that are ultimately justified by observation of the world.

Where conflicts now sometimes arise between mathematicians and scientists, it is generally over the issue of mathematical rigor. Since the early nineteenth century, researchers in pure mathematics have regarded rigor as essential; definitions and assumptions must be precise, and deductions must follow with absolute certainty. Physicists are more opportunistic, demanding only enough precision and certainty to give them a good chance of avoiding serious mistakes. In the preface of my own treatise on the quantum theory of fields, I admit that "there are parts of this book that will bring tears to the eyes of the mathematically inclined reader."

This leads to problems in communication. Mathematicians have told me that they often find the literature of physics infuriatingly vague. Physicists like myself who need advanced mathematical tools often find that the mathematicians' search for rigor makes their writings complicated in ways that are of little physical interest.

There has been a noble effort by mathematically inclined physicists to put the formalism of modern elementary particle physics—the quantum theory of fields—on a mathematically rigorous basis, and some interesting progress has been made. But nothing in the development over the past half century of the Standard Model of elementary particles has depended on reaching a higher level of mathematical rigor.

Greek mathematics continued to thrive after Euclid. In Chapter 4 we will come to the great achievements of the later Hellenistic mathematicians Archimedes and Apollonius.

purpose underlying their evolution. They are what they are because they have been naturally selected over millions of years of undirected inheritable variations. And of course, long before Darwin, physicists had learned to study matter and force without asking about the purpose they serve.

Aristotle's early concern with zoology may also have inspired his strong emphasis on taxonomy, on sorting things out in categories. We still use some of this, for instance the Aristotelian classification of governments into monarchies, aristocracies, and not democracies but constitutional governments. But much of it seems pointless. I can imagine how Aristotle might have classified fruits: *All fruits come in three varieties—there are apples, and oranges, and fruits that are neither apples nor oranges.*

One of Aristotle's classifications was pervasive in his work, and became an obstacle for the future of science. He insisted on the distinction between the natural and the artificial. He begins Book II of *Physics*[4] with "Of things that exist, some exist by nature, some from other causes." It was only the natural that was worthy of his attention. Perhaps it was this distinction between the natural and the artificial that kept Aristotle and his followers from being interested in experimentation. What is the good of creating an artificial situation when what are really interesting are natural phenomena?

It is not that Aristotle neglected the observation of natural phenomena. From the delay between seeing lightning and hearing thunder, or seeing oars on a distant trireme striking the water and hearing the sound they make, he concluded that sound travels at a finite speed.[5] We will see that he also made good use of observation in reaching conclusions about the shape of the Earth and about the cause of rainbows. But this was all casual observation of natural phenomena, not the creation of artificial circumstances for the purpose of experimentation.

The distinction between the natural and artificial played a large role in Aristotle's thought about a problem of great importance in the history of science—the motion of falling bodies. Aristotle taught that solid bodies fall down because the natural place of the element earth is downward, toward the center of the cosmos, and sparks fly upward because the natural place of fire is in the heavens. The Earth is nearly a sphere, with its center at the center of the cosmos, because this allows the greatest proportion of earth to approach that center. Also, allowed to fall naturally, a falling body has a speed proportional to its weight. As we read in *On the Heavens*,[6] according to Aristotle, "A given weight moves a given distance in a given time; a weight which is as great and more moves the same distance in a less time, the times being in inverse proportion to the weights. For instance, if one weight is twice another, it will take half as long over a given movement."

Aristotle can't be accused of entirely ignoring the observation of falling bodies. Though he did not know the reason, the resistance of air or any other medium surrounding a falling body has the effect that the speed eventually approaches a constant value, the terminal velocity, which does increase with the falling body's weight. (See Technical Note 6.) Probably more important to Aristotle, the observation that the speed of a falling body increases with its weight fitted in well with his notion that the body falls because the natural place of its material is toward the center of the world.

For Aristotle, the presence of air or some other medium was essential in understanding motion. He thought that without any resistance, bodies would move at infinite speed, an absurdity that led him to deny the possibility of empty space. In *Physics,* he argues, "Let us explain that there is no void existing separately, as some maintain."[7] But in fact it is only the terminal velocity of a falling body that is inversely proportional to the resistance. The terminal velocity would indeed be infinite in the absence of all resistance, but in that case a falling body would never reach terminal velocity.

In the same chapter Aristotle gives a more sophisticated argument, that in a void there would be nothing to which motion could be relative: "in the void things must be at rest; for there is no place to which things can move more or less than to another; since the void in so far as it is void admits no difference."[8] But this is an argument against only an infinite void; otherwise motion in a void can be relative to whatever is outside the void.

Because Aristotle was acquainted with motion only in the presence of resistance, he believed that all motion has a cause.* (Aristotle distinguished four kinds of cause: material, formal, efficient, and final, of which the final cause is teleological—it is the purpose of the change.) That cause must itself be caused by something else, and so on, but the sequence of causes cannot go on forever. We read in *Physics*,[9] "Since everything that is in motion must be moved by something, let us take the case in which a thing is in locomotion and is moved by something that is itself in motion, and that again is moved by something else that is in motion, and that by something else, and so on continually; then the series cannot go on to infinity, but there must be some first mover." The doctrine of a first mover later provided Christianity and Islam with an argument for the existence of God. But as we will see, in the Middle Ages the conclusion that God could not make a void raised troubles for followers of Aristotle in both Islam and Christianity.

Aristotle was not bothered by the fact that bodies do not always move toward their natural place. A stone held in the hand does not fall, but for Aristotle this just showed the effect of artificial interference with the natural order. But he was seriously worried over the fact that a stone thrown upward continues for a while to rise, away from the Earth, even after it has left the hand. His explanation, really no explanation, was that the stone continues upward for a while because of the motion given to it by the air. In Book III of *On the Heavens*, he explains that "the force transmits the movement to the body by first, as it were, tying it up in the air. That is why a body moved by constraint continues to move even when that which gave it the impulse ceases to accompany it."[10] As we will see, this notion was frequently discussed and rejected in ancient and medieval times.

Aristotle's writing on falling bodies is typical at least of his physics—elaborate though non-mathematical reasoning based on assumed first principles, which are themselves based on only the most casual observation of nature, with no effort to test them.

I don't mean to say that Aristotle's philosophy was seen by his followers and successors as an alternative to science. There was no conception in the ancient or medieval world of science as something distinct from philosophy. Thinking about the natural world *was* philosophy. As late as the nineteenth century, when German universities instituted a doctoral degree for scholars of the arts and sciences to give them equal status with doctors of theology, law, and medicine, they invented the title “doctor of philosophy.” When philosophy had earlier been compared with some other way of thinking about nature, it was contrasted not with science, but with mathematics.

No one in the history of philosophy has been as influential as Aristotle. As we will see in Chapter 9, he was greatly admired by some Arab philosophers, even slavishly so by Averroes. Chapter 10 tells how Aristotle became influential in Christian Europe in the 1200s, when his thought was reconciled with Christianity by Thomas Aquinas. In the high Middle Ages Aristotle was known simply as “The Philosopher,” and Averroes as “The Commentator.” After Aquinas the study of Aristotle became the center of university education. In the Prologue to Chaucer’s *Canterbury Tales*, we are introduced to an Oxford scholar:

> *A Clerk there was of Oxenford also …*
> *For he would rather have at his bed’s head*
> *Twenty books, clad in black or red,*
> *Of Aristotle, and his philosophy,*
> *Than robes rich, or fiddle, or gay psaltery.*

Of course, things are different now. It was essential in the discovery of science to separate science from what is now called philosophy. There is active and interesting work on the philosophy *of* science, but it has very little effect on scientific research.

The precocious scientific revolution that began in the fourteenth century and is described in Chapter 10 was largely a revolt against Aristotelianism. In recent years students of Aristotle have mounted something of a counterrevolution. The very influential historian Thomas Kuhn described how he was converted from disparagement to admiration of Aristotle:[11]

> About motion, in particular, his writings seemed to me full of egregious errors, both of logic and of observation. These conclusions were, I felt, unlikely. Aristotle, after all, had been the

> much-admired codifier of ancient logic. For almost two millennia after his death, his work played the same role in logic that Euclid's played in geometry.… How could his characteristic talent have deserted him so systematically when he turned to the study of motion and mechanics? Equally, why had his writings in physics been taken so seriously for so many centuries after his death? … Suddenly the fragments in my head sorted themselves out in a new way, and fell in place together. My jaw dropped with surprise, for all at once Aristotle seemed a very good physicist indeed, but of a sort I'd never dreamed possible.… I had suddenly found the way to read Aristotelian texts.

I heard Kuhn make these remarks when we both received honorary degrees from the University of Padua, and later asked him to explain. He replied, "What was altered by my own first reading of [Aristotle's writings on physics] was my understanding, not my evaluation, of what they achieved." I didn't understand this: "a very good physicist indeed" seemed to me like an evaluation.

Regarding Aristotle's lack of interest in experiment: the historian David Lindberg[12] remarked, "Aristotle's scientific practice is not to be explained, therefore, as a result of stupidity or deficiency on his part—failure to perceive an obvious procedural improvement—but as a method compatible with the world as he perceived it and well suited to the questions that interest him." On the larger issue of how to judge Aristotle's success, Lindberg added, "It would be unfair and pointless to judge Aristotle's success by the degree to which he anticipated modern science (as though his goal was to answer our questions, rather than his own)." And in a second edition of the same work:[13] "The proper measure of a philosophical system or a scientific theory is not the degree to which it anticipated modern thought, but its degree of success in treating the philosophical and scientific problems of its own day."

I don't buy it. What is important in science (I leave philosophy to others) is not the solution of some popular scientific problems of one's own day, but understanding the world. In the course of this work, one finds out what sort of explanations are possible, and what sort of problems can lead to those explanations. The progress of science has been largely a matter of discovering what questions should be asked.

and later, in the Roman Empire, it was second only to Rome in size and wealth.

Around 300 BC Ptolemy I founded the Museum of Alexandria, as part of his royal palace. It was originally intended as a center of literary and philological studies, dedicated to the nine Muses. But after the accession of Ptolemy II in 285 BC the Museum also became a center of scientific research. Literary studies continued at the Museum and Library of Alexandria, but now at the Museum the eight artistic Muses were outshone by their one scientific sister —Urania, the Muse of astronomy. The Museum and Greek science outlasted the kingdom of the Ptolemies, and, as we shall see, some of the greatest achievements of ancient science occurred in the Greek half of the Roman Empire, and largely in Alexandria.

The intellectual relations between Egypt and the Greek homeland in Hellenistic times were something like the connections between America and Europe in the twentieth century.[2] The riches of Egypt and the generous support of at least the first three Ptolemies brought to Alexandria scholars who had made their names in Athens, just as European scholars flocked to America from the 1930s on. Starting around 300 BC, a former member of the Lyceum, Demetrius of Phaleron, became the first director of the Museum, bringing his library with him from Athens. At around the same time Strato of Lampsacus, another member of the Lyceum, was called to Alexandria by Ptolemy I to serve as tutor to his son, and may have been responsible for the turn of the Museum toward science when that son succeeded to the throne of Egypt.

The sailing time between Athens and Alexandria during the Hellenistic and Roman periods was similar to the time it took for a steamship to go between Liverpool and New York in the twentieth century, and there was a great deal of coming and going between Egypt and Greece. For instance, Strato did not stay in Egypt; he returned to Athens to become the third director of the Lyceum.

Strato was a perceptive observer. He was able to conclude that falling bodies accelerate downward, by observing how drops of water falling from a roof become farther apart as they fall, a continuous stream of water breaking up into separating drops. This is because the drops that have fallen farthest have also been falling longest, and since they are accelerating this means that they are traveling faster than drops following them, which have been falling for a shorter time. (See Technical Note 7.) Strato noted also that when a body falls a very short distance the impact on the ground is negligible, but if it falls from a great height it makes a powerful impact, showing that its speed increases as it falls.[3]

It is probably no coincidence that centers of Greek natural philosophy like Alexandria as well as Miletus and Athens were also centers of commerce. A lively market brings together people from different cultures, and relieves the monotony of agriculture. The commerce of Alexandria was far-ranging: seaborne cargoes being taken from India to the Mediterranean world would cross the Arabian Sea, go up the Red Sea, then go overland to the Nile and down the Nile to Alexandria.

But there were great differences in the intellectual climates of Alexandria and Athens. For one thing, the scholars of the Museum generally did not pursue the kind of all-embracing theories that had preoccupied the Greeks from Thales to Aristotle. As Floris Cohen has remarked,[4] “Athenian thought was comprehensive, Alexandrian piecemeal.” The Alexandrians concentrated on understanding specific phenomena, where real progress could be made. These topics included optics and hydrostatics, and above all astronomy, the subject of Part II.

It was no failing of the Hellenistic Greeks that they retreated from the effort to formulate a general theory of everything. Again and again, it has been an essential feature of scientific progress to understand which problems are ripe for study and which are not. For instance, leading physicists at the turn of the twentieth century, including Hendrik Lorentz and Max Abraham, devoted themselves to understanding the structure of the recently discovered electron. It was hopeless; no one could have made progress in understanding the nature of the electron before the advent of quantum mechanics some two decades later. The development of the special theory of relativity by Albert Einstein was made possible by Einstein's refusal to worry about what electrons are. Instead he worried about how observations of anything (including electrons) depend on the motion of the observer. Then Einstein himself in his later years addressed the problem of the unification of the forces of nature, and made no progress because no one at the time knew enough about these forces.

Another important difference between Hellenistic scientists and their Classical predecessors is that the Hellenistic era was less afflicted by a snobbish distinction between knowledge for its own sake and knowledge for use—in Greek, *episteme* versus *techne* (or in Latin, *scientia* versus *ars*). Throughout history, many philosophers have viewed inventors in much the same way that the court chamberlain Philostrate in *A Midsummer Night's Dream* described Peter Quince and his actors: "Hard-handed men, who work now in Athens, and never yet labor'd with their minds." As a physicist whose research is on subjects like elementary particles and cosmology that have no immediate practical application, I am certainly not going to say anything against knowledge for its own sake, but doing scientific research to fill human needs has a wonderful way of forcing the scientist to stop versifying and to confront reality.[5]

Of course, people have been interested in technological improvement since early humans learned how to use fire to cook food and how to make simple tools by banging one stone on another. But the persistent intellectual snobbery of the Classical intelligentsia kept philosophers like Plato and Aristotle from directing their theories toward technological applications.

Though this prejudice did not disappear in Hellenistic times, it became less influential. Indeed, people, even those of ordinary birth, could become famous as inventors. A good example is Ctesibius of Alexandria, a barber's son, who around 250 BC invented suction and force pumps and a water clock that kept time more accurately than earlier water clocks by keeping a constant level of water in the vessel from which the water flowed. Ctesibius was famous enough to be remembered two centuries later by the Roman Vitruvius in his treatise *On Architecture.*

It is important that some technology in the Hellenistic age was developed by scholars who were also concerned with systematic scientific inquiries, inquiries that were sometimes themselves used in aid of technology. For instance, Philo of Byzantium, who spent time in Alexandria around 250 BC, was a military engineer who in *Mechanice syntaxism* wrote about harbors, fortifications, sieges, and catapults (work based in part on that of Ctesibius). But in *Pneumatics*, Philo also gave experimental arguments supporting the view of Anaximenes, Aristotle, and Strato that air is real. For instance, if an empty bottle is submerged in water with its mouth open but facing downward, no water will flow into it, because there is nowhere for the air in the bottle to go; but if a hole is opened so that air is allowed to leave the bottle, then water will flow in and fill the bottle.[6]

There was one scientific subject of practical importance to which Greek scientists returned again and again, even into the Roman period: the behavior of light. This concern dates to the beginning of the Hellenistic era, with the work of Euclid.

Little is known of the life of Euclid. He is believed to have lived in the time of Ptolemy I, and may have founded the study of mathematics at the Museum in Alexandria. His best-known work is the *Elements*,[7] which begins with a number of geometric definitions, axioms, and postulates, and moves on to more or less rigorous proofs of increasingly sophisticated theorems. But Euclid also wrote the *Optics*, which deals with perspective, and his name is associated with the *Catoptrics*, which studies reflection by mirrors, though modern historians do not believe that he was its author.

When one thinks of it, there is something peculiar about reflection. When you look at the reflection of a small object in a flat mirror, you see the image at a definite spot, not spread out over the mirror. Yet there are many paths one can draw from the object to various spots on the mirror and then to the eye.* Apparently there is just one path that is actually taken, so that the image appears at the one point where this path strikes the mirror. But what determines the location of that point on the mirror? In the *Catoptrics* there appears a fundamental principle that answers this question: the angles that a light ray makes with a flat mirror when it strikes the mirror and when it is reflected are equal. Only one light path can satisfy this condition.

We don't know who in the Hellenistic era actually discovered this principle. We do know, though, that sometime around AD 60 Hero of Alexandria in his own *Catoptrics* gave a mathematical proof of the equal-angles rule, based on the assumption that the path taken by a light ray in going from the object to the mirror and then to the eye of the observer is the path of shortest length. (See Technical Note 8.) By way of justification for this principle, Hero was content to say only, "It is agreed that Nature does nothing in vain, nor exerts herself needlessly."[8] Perhaps he was motivated by the teleology of Aristotle—everything happens for a purpose. But Hero was right; as we will see in Chapter 14, in the seventeenth century Huygens was able to deduce the principle of shortest distance (actually shortest time) from the wave nature of light. The same Hero who explored the fundamentals of optics used that knowledge to invent an instrument of practical surveying, the theodolite, and also explained the action of siphons and designed military catapults and a primitive steam engine.

The study of optics was carried further about AD 150 in Alexandria by the great astronomer Claudius Ptolemy (no kin of the kings). His book *Optics* survives in a Latin translation of a lost Arabic version of the lost Greek original (or perhaps of a lost Syriac intermediary). In this book Ptolemy described measurements that verified the equal-angles rule of Euclid and Hero. He also applied this rule to reflection by curved mirrors, of the sort one finds today in amusement parks. He correctly understood that reflections in a curved mirror are just the same as if the mirror were a plane, tangent to the actual mirror at the point of reflection.

In the final book of *Optics* Ptolemy also studied refraction, the bending of light rays when they pass from one transparent medium such as air to another transparent medium such as water. He suspended a disk, marked with measures of angle around its edge, halfway in a vessel of water. By sighting a submerged object along a tube mounted on the disk, he could measure the

Cicero said that he had seen on the tombstone of Archimedes a cylinder circumscribed about a sphere, the surface of the sphere touching the sides and both bases of the cylinder, like a single tennis ball just fitting into a tin can. Apparently Archimedes was most proud of having proved that in this case the volume of the sphere is two-thirds the volume of the cylinder.

There is an anecdote about the death of Archimedes, related by the Roman historian Livy. Archimedes died in 212 BC during the sack of Syracuse by Roman soldiers under Marcus Claudius Marcellus. (Syracuse had been taken over by a pro-Carthaginian faction during the Second Punic War.) As Roman soldiers swarmed over Syracuse, Archimedes was supposedly found by the soldier who killed him, while he was working out a problem in geometry.

Aside from the incomparable Archimedes, the greatest Hellenistic mathematician was his younger contemporary Apollonius. Apollonius was born around 262 BC in Perga, a city on the southeast coast of Asia Minor, then under the control of the rising kingdom of Pergamon, but he visited Alexandria in the times of both Ptolemy III and Ptolemy IV, who between them ruled from 247 to 203 BC. His great work was on conic sections: the ellipse, parabola, and hyperbola. These are curves that can be formed by a plane slicing through a cone at various angles. Much later, the theory of conic sections was crucially important to Kepler and Newton, but it found no physical applications in the ancient world.

Brilliant work, but with its emphasis on geometry, there were techniques missing from Greek mathematics that are essential in modern physical science. The Greeks never learned to write and manipulate algebraic formulas. Formulas like $E = mc^2$ and $F = ma$ are at the heart of modern physics. (Formulas were used in purely mathematical work by Diophantus, who flourished in Alexandria around AD 250, but the symbols in his equations were restricted to standing for whole or rational numbers, quite unlike the symbols in the formulas of physics.) Even where geometry is important, the modern physicist tends to derive what is needed by expressing geometric facts algebraically, using the techniques of analytic geometry invented in the seventeenth century by René Descartes and others, and described in Chapter 13. Perhaps because of the deserved prestige of Greek mathematics, the geometric style persisted until well into the scientific revolution of the seventeenth century. When Galileo in his 1623 book *The Assayer* wanted to sing the praises of mathematics, he spoke of geometry:* "Philosophy is written in this all-encompassing book that is constantly open to our eyes, that is the universe; but it cannot be understood unless one first learns to understand the language and knows the characters in which it is written. It is written in mathematical language, and its characters are triangles, circles, and other geometrical figures; without these it is humanly impossible to understand a word of it, and one wanders in a dark labyrinth." Galileo was somewhat behind the times in emphasizing geometry over algebra. His own writing uses some algebra, but is more geometric than that of some of his contemporaries, and far more geometric than what one finds today in physics journals.

In modern times a place has been made for pure science, science pursued for its own sake without regard to practical applications. In the ancient world, before scientists learned the necessity of verifying their theories, the technological applications of science had a special importance, for when one is going to use a scientific theory rather than just talk about it, there is a large premium on getting it right. If Archimedes by his measurements of specific gravity had identified a gilded lead crown as being made of solid gold, he would have become unpopular in Syracuse.

I don't want to exaggerate the extent to which science-based technology was important in Hellenistic or Roman times. Many of the devices of Ctesibius and Hero seem to have been no more than toys, or theatrical props. Historians have speculated that in an economy based on slavery there was no demand for labor-saving devices, such as might have been developed from Hero's toy steam engine. Military and civil engineering *were* important in the ancient world, and the kings in Alexandria supported the study of catapults and other artillery, perhaps at the Museum, but this work does not seem to have gained much from the science of the time.

The one area of Greek science that did have great practical value was also the one that was most highly developed. It was astronomy, to which we will turn in Part II.

There is a large exception to the remark above that the existence of practical applications of science provided a strong incentive to get the science right. It is the practice of medicine. Until modern times the most highly regarded physicians persisted in practices, like bleeding, whose value had never been established experimentally, and that in fact did more harm than good. When in the nineteenth century the really useful technique of antisepsis was introduced, a technique for which there *was* a scientific basis, it was at first actively resisted by most physicians. Not until well into the twentieth century were clinical trials required before medicines could be approved for use. Physicians did learn early on to recognize various diseases, and for some they had effective remedies, such as Peruvian bark—which contains quinine—for malaria. They knew how to prepare analgesics, opiates, emetics, laxatives, soporifics, and poisons. But it is often remarked that until sometime around the beginning of the twentieth century the average sick person would do better avoiding the care of physicians.

It is not that there was no theory behind the practice of medicine. There was humorism, the theory of the four humors—blood, phlegm, black bile, and yellow bile, which (respectively) make us sanguine, phlegmatic, melancholy, or choleric. Humorism was introduced in classical Greek times by Hippocrates, or by colleagues of his whose writings were ascribed to him. As briefly stated much later by John Donne in “The Good Morrow,” the theory held that “whatever dies was not mixed equally.” The theory of humorism was adopted in Roman times by Galen of Pergamon, whose writings became enormously influential among the Arabs and then in Europe after about AD 1000. I am not aware of any effort while humorism was generally accepted ever to test its effectiveness experimentally. (Humorism survives today in Ayurveda, traditional Indian medicine, but with just three humors: phlegm, bile, and wind.)

In addition to humorism, physicians in Europe until modern times were expected to understand another theory with supposed medical applications: astrology. Ironically, the opportunity for physicians to study these theories at universities gave medical doctors much higher prestige than surgeons, who knew how to do really useful things like setting broken bones but until modern times were not usually trained in universities.

So why did the doctrines and practices of medicine continue so long without correction by empirical science? Of course, progress is harder in biology than in astronomy. As we will discuss in Chapter 8, the apparent motions of the Sun, Moon, and planets are so regular that it was not difficult to see that an early theory was not working very well; and this perception led, after a few centuries, to a better theory. But if a patient dies despite the best efforts of a learned physician, who can say what is the cause? Perhaps the patient waited too long to see the doctor. Perhaps he did not follow the doctor’s orders with sufficient care.

At least humorism and astrology had an air of being scientific. What was the alternative? Going back to sacrificing animals to Aesculapius?

Another factor may have been the extreme importance to patients of recovery from illness. This gave physicians authority over them, an authority that physicians had to maintain in order to impose their supposed remedies. It is not only in medicine that persons in authority will resist any investigation that might reduce their authority.