Columbus' voyages are one example of the fruitfulness of a conceptual scheme. They show how theories can guide a scientist into the unknown, telling him where to look and what he may expect to find, and this is perhaps the single most important function of conceptual schemes in science. But the guidance provided by conceptual schemes is rarely so direct and unequivocal as that illustrated above. Typically a conceptual scheme provides hints for the organization of research rather than explicit directives, and the pursuit of these hints usually requires extension or modification of the conceptual scheme that provided them. For example, the two-sphere universe was initially developed principally to account for the diurnal motions of the stars and for the way in which those motions varied with the observer's location on the earth. But once it had been developed, the new theory was readily extended to give order and simplicity to observations of the sun's motion as well. And, having disclosed the unsuspected regularity that underlay the complexity of the sun's behavior, the conceptual scheme provided a framework within which could be studied the even more irregular motions of the planets. That problem had seemed unmanageable until the over-all motion of the heavens was reduced to order.

Much of this book will be concerned with the fruitfulness of particular conceptual schemes, that is, with their effectiveness as guides for research and as frameworks for the organization of knowledge. The next two chapters, in particular, will examine the role of the two-sphere universe in the ancient solution, first, of the problem of the planets and, then, of some problems lying entirely outside astronomy. Later we shall discover the rather different sort of guidance given to scientific research by Copernicus' novel conception of a moving planetary earth. The very best example of fruitfulness is, however, the story told in the whole of this book. The Copernican universe is itself the product of a series of investigations that the two-sphere universe made possible: the conception of a planetary earth is the most forceful illustration of the effective guidance given to science by the incompatible conception of a unique central earth. That is why a discussion of the Copernican Revolution must begin with a study of the two-sphere cosmology which Copernicanism ultimately made obsolete. The two-sphere universe is the parent of the Copernican; no conceptual scheme is born from nothing.

Ancient Competitors of the Two-Sphere Universe

The two-sphere conception of the universe was not the only cosmology suggested in ancient Greece. But it was the one taken most seriously by the largest number of people, particularly by astronomers, and it was the one that later Western civilization first inherited from the Greeks. Yet many of the alternate cosmologies proposed and rejected in antiquity show far closer resemblances to modern cosmological beliefs than does the two-sphere universe. Nothing more clearly illustrates the strengths of the two-sphere cosmology and foreshadows the difficulties to be encountered in overthrowing it than a compari-

Leucippus and Democritus

son of the scheme with a few of its superficially more modern alternatives.

As early as the fifth century B.C., the Greek atomists, Leucippus and Democritus, visualized the universe as an infinite empty space, populated by an infinite number of minute indivisible particles or atoms moving in all directions. In their universe the earth was but one of many essentially similar heavenly bodies formed by the chance aggregation of atoms. It was not unique, nor at rest, nor at the center. In fact, an infinite universe has no center; each part of space is like every other; therefore the infinite number of atoms, some of which aggregated to form our earth and sun, must have formed numerous other worlds in other portions of the empty space or void. For the atomists there were other suns and other earths among the stars.

Later in the fifth century the followers of Pythagoras suggested a second cosmology which set the earth in motion and partially deprived it of its unique status. The Pythagoreans did place the stars on a gigantic moving sphere, but at the center of this sphere they placed an immense fire, the Altar of Zeus, invisible from the earth. The fire could not be seen, because the earth's populated areas were always turned away from the fire. For the Pythagoreans the earth was just one of a number of celestial bodies, including the sun, all of which moved in circles about the central fire. A century later Heraclides of Pontus (fourth century B.C.) suggested that it was a daily rotation of the central earth rather than a rotation of the peripheral sphere of the stars that produced the apparent motion of the heavens. He also obscured the symmetry of the two-sphere universe by suggesting that the planets Mercury and Venus revolved in circles about the moving sun rather than in independent circular orbits about the central earth (see Chapter 2). Still later, in the middle of the third century B.C., Aristarchus of Samos, whose ingenious and influential measurements of astronomical dimensions are described in the Technical Appendix, advanced the proposal that has earned for him the title of "the Copernicus of antiquity." For Aristarchus the sun was at the center of an immensely expanded sphere of the stars, and the earth moved in a circle about the sun.

These alternative cosmologies, particularly the first and last, are remarkably like our modern views. We do believe today that the earth is but one of a number of planets, circulating about the sun, and that the sun is but one of a multitude of stars, some of which may have their own planets. But though some of these speculative suggestions gave rise to significant minority traditions in antiquity, and though all of them were a continuing source of intellectual stimulus to innovators like Copernicus, they were not originally supported by the arguments that now make us believe them, and in the absence of these arguments they were rejected by most philosophers and almost all astronomers in the ancient world. In the Middle Ages they were ridiculed or ignored. The reasons for the rejection were excellent. These alternative cosmologies violate the first and most fundamental suggestions provided by the senses about the structure of the universe. Furthermore, this violation of common sense is not compensated for by any increase in the effectiveness with which they account for the appearances. At best they are no more economical, fruitful, or precise than the two-sphere universe, and they are a great deal harder to believe. It was difficult to take them seriously as explanations.

All of these alternative cosmologies take the motion of the earth as a premise, and all (except Heraclides' system) make the earth move as one of a number of heavenly bodies. But the first distinction suggested by the senses is that separating the earth and the heavens. The earth is not part of the heavens; it is the platform from which we view them. And the platform shares few or no apparent characteristics with the celestial bodies seen from it. The heavenly bodies seem bright points of light, the earth an immense nonluminous sphere of mud and rock. Little change is observed in the heavens: the stars are the same night after night and apparently have remained so throughout the many centuries covered by ancient records. In contrast the earth is the home of birth and change and destruction. Vegetation and animals alter from week to week; civilizations rise and fall from century to century; legends attest the slower topographical changes produced on earth by flood and storm. It seems absurd to make the earth like celestial bodies whose most prominent characteristic is that immutable regularity never to be achieved on the corruptible earth.

The idea that the earth moves seems initially equally absurd. Our senses tell us all we know of motion, and they indicate no motion for the earth. Until it is reëducated, common sense tells us that, if the earth is in motion, then the air, clouds, birds, and other objects not attached to the earth must be left behind. A man jumping would descend to earth far from the point where his leap began, for the earth would move beneath him while he was in the air. Rocks and trees, cows and men must be hurled from a rotating earth as a stone flies from a rotating sling. Since none of these effects is seen, the earth is at rest. Observation and reason have combined to prove it.

Today in the Western world only children argue this way, and only children believe that the earth is at rest. At an early age the authority of teachers, parents, and texts persuades them that the earth is really a planet and in motion; their common sense is reëducated; and the arguments born from everyday experience lose their force. But reëducation is essential — in its absence these arguments are immensely persuasive — and the pedagogic authorities that we and our children accept were not available to the ancients. The Greeks could only rely on observation and reason, and neither produced evidence for the earth's motion. Without the aid of telescopes or of elaborate mathematical arguments that have no apparent relation to astronomy, no effective evidence for a moving planetary earth can be produced. The observations available to the naked eye fit the two-sphere universe very well (remember the universe of the practical navigator and surveyor), and there is no more natural explanation of them. It is not hard to realize why the ancients believed in the two-sphere universe. The problem is to discover why the conception was given up.