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THE FOUNDATIONS OF MODERN SCIENCE IN THE MIDDLE AGES

Their religious, institutional, and intellectual contexts

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identifiable contributions to the transformation of the exact sciences in the Scientific Revolution.

I intend this study to be a relatively brief, interpretive essay for a broad audience. Therefore, I have limited footnotes almost exclusively to the identification of quotations. Also, I would like to thank the anonymous reader who reviewed my manuscript for the Cambridge University Press. Despite our radically different attitudes toward history in general, and the Middle Ages in particular, I profited from a number of helpful suggestions and corrections and am still awed by the diligence and dedication with which he or she carried out this difficult assignment.

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The Roman Empire and the first six centuries of Christianity

DURING the first four centuries of Christianity, the Roman Empire was a geographical colossus, extending from the Atlantic Ocean in the west to Persia in the east, and from Britain in the north to regions south of the Mediterranean Sea. Within this Greco-Roman world, Christianity was born and disseminated. Its birth and early development occurred in a period of vast religious change and economic upheaval. For the first two hundred years of its existence, Christianity was no more visible and noticeable than many other of the numerous mystery religions and cults that had proven attractive to people at all levels of society. The sense of comfort that pagans derived from their belief in the traditional Homeric and Roman gods of the state religions was disappearing. The new cults – for example, Isis, Mithras, Cybele, and Sol Invictus (Unconquered Sun), as well as Gnosticism and Christianity – that were replacing the traditional deities not only borrowed ideas and rituals from one another but also came to share a few basic beliefs. The world was evil and would eventually pass away. Humans, sinful by nature, could achieve never-ending bliss only if they turned away from the things of this world and cultivated those of the eternal spiritual realm. Along with practicing varying degrees of asceticism, many of the cults believed in a redeemer god who would die in order to bring eternal life after death to his faithful followers. Contemporary philosophical schools, such as Neoplatonism and Neopythagoreanism, were also affected by these popular currents. Some came to function as religions, as they sought to guide their adherents toward salvation and union with God, even employing magic to achieve their ends. (The philosophical schools, however, were ill-suited to the competition, because they required lengthy periods of study and training before they judged a student capable of understanding the world and its governance.) The reaction to centuries of homogenized and impersonal worship of traditional gods took the form of a desire for a single, personal god, the ruler of the world, with whom one could establish an intimate, personal relationship. Many came to believe that they could be transformed by a direct revelation from the one god, a revelation that would enable them to overcome the evils of the world. Numerous groups emerged, each concerned with its own private and exclusive program for salvation. Christianity was one of these.

How Christianity triumphed over the traditional gods and also over the numerous other mystery religions and cults that were its rivals cannot be discussed here. But certain features that concern Christianity's dissemination and its attitude toward the larger Roman world around it are germane to the subsequent development of science and therefore central to this volume. A notable feature of the spread of Christianity was the slowness of its dissemination. The spread of Christianity beyond the Holy Land and its surrounding region began in earnest after Saint Paul proselytized into the Gentile world, especially into Greece, during the middle of the first century. In retrospect – and by comparison with the spread of Islam – the pace of the dissemination of Christianity appears quite slow. Not until A.D. 300 was Christianity effectively represented throughout the Roman Empire. And not until 313, in the reign of Constantine, was the Edict of Milan (or Edict of Toleration) issued, which conferred on Christianity full legal equality with all other religions in the empire. In 392, the Emperor Theodosius not only ordered pagan temples closed but also proscribed pagan worship, which thereafter was classified as treason. Thus it was not until 392, or the end of the fourth century, that Christianity became the exclusive religion supported by the state. After almost four centuries, Christianity was triumphant. It had taken nearly four centuries (approximately three hundred fifty years from the beginning of Paul's serious efforts to spread Christianity wherever possible) to achieve this result. By contrast, Islam, following the death of Muhammad in 632, was carried over an enormous geographical area in a remarkably short time. In less than one hundred years, Islam was the dominant religion from the Arabian peninsula westward to the Straits of Gibraltar, northward to Spain, and eastward to Persia, Balkh, Bukhara, Samarkand, and Khwarizm. But where Islam was spread largely by conquest during its first one hundred years, Christianity spread slowly and, with the exception of certain periods of persecution, relatively peacefully. It was the slow percolation of Christianity that enabled it to adjust to the pagan world around it and thus prepare itself for a role that could not have been envisioned by its early members.

CHRISTIANITY AND PAGAN LEARNING

The momentous adjustment of Christianity to the pagan world around it is manifested by numerous learned Christians whose writings were subsequently influential. To Gregory of Nyssa, Christianity was "the sublime philosophy." Yet he, like many other eminent Christians, recognized that pagan philosophy still had a role to play, as did pagan tradition and learning generally. In the process of acquiring an education, Christians came to share numerous cultural traditions with their pagan neighbors and fellow citizens. Much of this came by way of *paideia*, a kind of shared civility, which "offered ancient, almost proverbial guidance, drawn from the history and literature of Greece, on serious issues, issues which no notable – Christian or polytheist, bishop or layman – could afford to ignore: on courtesy, on the prudent administration of friendship, on the control of anger, on poise and persuasive skill when faced by official violence."[1]

Because they came from varied backgrounds, the Greek fathers, who significantly shaped Christian attitudes toward pagan philosophy, were hardly of one mind on the subject. Some were hostile to science and philosophy out of concern for their potentially subversive effect on the faith. Most, however, denounced these disciplines because of their conviction that Christianity was "the sublime philosophy" and therefore the only system capable of delivering truth. For many of them, science was a confusing, contradictory body of knowledge. Church fathers like Tatian, Eusebius, Theodoret, and Saint Basil seemingly delighted in subverting Greek science by showing that its conclusions were often fatuous or contradictory. Theodoret likened science to writing on water,[2] and Basil declared, perhaps in imitation of Plato's scornful description of the Presocratics, that "the wise men of the Greeks wrote many works about nature, but not one account among them remained unaltered and firmly established, for the later account always overthrew the preceding one. As a consequence there is no need for us to refute their words; they avail mutually for their own undoing."[3] Many church fathers, of whom Gregory of Nyssa was one, followed Plato and argued that science could at best give only probable knowledge, not genuine truth.

As early as the end of the second century and first half of the third century, other Christian apologists came to a quite different conclusion, arguing instead that Christianity could profitably utilize pagan Greek philosophy and learning. In a momentous move, Clement of Alexandria (ca. 150–ca. 215) and his disciple Origen of Alexandria (ca. 185–ca. 254) laid down the basic approach that others would follow. Greek philosophy was neither inherently good nor bad, but was one or the other depending on how it was used by Christians. Although the Greek poets and philosophers had not received direct revelation from God, they did receive natural reason and were thus heading toward truth. Philosophy – and secular learning in general – could thus be used to prepare the way for Christian wisdom, which was the fruit of revelation. Philosophy and science could be studied as "handmaidens to theology," that is, as aids in understanding Holy Scripture, an attitude that had already been advocated by Philo Judaeus, a resident of the Jewish community of Alexandria, early in the first century A.D. Science was thus regarded as a study that was preparatory for the higher disciplines that were concerned with Scripture and theology. In the second half of the fourth century, Basil of Caesarea reinforced the handmaiden idea in a brief treatise to students titled *On How to Make Good Use of the Study of Greek Literature*. Like many of his early Christian colleagues, however, Basil was ambivalent. He warned about the dangers of some of the great works of Greek literature, but he also recognized that a Christian could profit from familiarity with pagan writings and quoted from various Greek works. Much later, Christian humanists in the Renaissance viewed Basil's treatise as providing encouragement for Christians to study pagan Greek literature. Leonardo Bruni (1370–1444) was inspired to translate Basil's treatise into Latin because he saw in it justification for his own translations of Plutarch and Plato from Greek to Latin.

The handmaiden concept of Greek learning was widely adopted and became the standard Christian attitude toward secular learning. That Christians chose to accept pagan learning within limits was a momentous decision. They might have heeded Tertullian (ca. 150–ca. 225), who asked pointedly, "What indeed has Athens to do with Jerusalem? What concord is there between the Academy and the Church?" With the total triumph of Christianity at the end of the fourth century, the Church might have reacted against Greek pagan learning in general, and Greek philosophy in particular, finding much in the latter that was unacceptable or perhaps even offensive. They might have launched a major effort to suppress pagan learning as a danger to the Church and its doctrines. But they did not. Why not?

Perhaps it was in the slow dissemination of Christianity. After four centuries as members of a distinct religion, Christians had learned to live with Greek secular learning and to utilize it for their own benefit. Their education was heavily infiltrated by Latin and Greek pagan literature and philosophy. Numerous converts to Christianity – the most notable being Saint Augustine – had been steeped in pagan learning, which formed a normal part of their societal and cultural milieu. Although Christians found certain aspects of pagan culture and learning unacceptable, they did not view them as a cancer to be cut out of the Christian body.

The handmaiden theory was obviously a compromise between rejection of traditional pagan learning and its full acceptance. By approaching secular learning with caution, Christians could utilize Greek philosophy – especially metaphysics – to better understand and explicate Holy Scripture and to cope with the difficulties generated by the assumption of the doctrine of the Trinity and other esoteric dogmas. Ordinary daily life also required use of the mundane sciences such as astronomy and mathematics. Christians realized that they could not turn their backs on Greek learning. But many were also wary of pagan Greek science and philosophy, which contained ideas and concepts that were contrary to Christian doctrine. Among these ideas were the common Greek notion that the world was eternal and had no beginning and the deterministic interpretations of the world advocated by Stoic philosophers and astrologers, who often assumed a world rigidly determined by the configurations of the planets and stars. Like Saint Basil a few years before him, Saint Augustine (354–430), who was enormously influential in the Latin Middle Ages, reflects both attitudes. He advocated the study of the liberal arts, including the sciences – geometry, arithmetic, astronomy, and music – embodied in the traditional quadrivium of the seven liberal arts. But he was suspicious of astronomy, a discipline that frequently led its practitioners to astrological determinism, which he deplored. Augustine's ambivalence toward secular learning is reflected in his *Retractions*, written in 426, four years before his death, where he expressed regret that he had ever emphasized the study of the seven liberal arts and concluded that the theoretical sciences and mechanical arts are of no use to a Christian.

HEXAEMERAL LITERATURE: CHRISTIAN COMMENTARIES ON THE CREATION ACCOUNT IN GENESIS

Although Christians adopted the handmaiden approach to science, science itself was not a major concern of theirs. However, their need to understand the Bible better and to explicate the creation account in Genesis made it advisable for Christians to learn something about natural philosophy and science. Following the pattern established by Philo Judaeus (d. ca. 40 A.D.), who left the first commentary on the creation account in Genesis, a number of influential church fathers – Saints Basil, Ambrose, and Augustine, for example – wrote commentaries that proved influential in the Middle Ages.

Basil (ca. 331–379), who wrote in Greek, presented his commentary in the form of nine homilies, delivered originally as lectures to audiences in a church. In this famous work, Basil sought to praise the glory and power of God and to instill in Christians a strong sense of moral purpose. To achieve these ends, he appealed to nature, as God's handiwork. In the process, he found it necessary to convey a modicum of contemporary scientific knowledge about the basic structure and composition of the world. For example, in explaining the words "In the beginning God created the heavens and the earth," Basil was compelled to consider a host of topics: whether creation was simultaneous, or in time; whether the heavens were created before the earth; the nature of the heavenly substance; the meaning of the firmament; the meaning of the waters above and below that firmament; clouds, vapors, and the four elements; the location and shape of the world; the production of vegetation on the earth; the creation of the planets and stars; and the creation of crawling creatures, birds, and sea life. Thus Basil confronted the question: how does the earth remain immobile at the center of the world? On what does it rest? Perhaps drawing on Aristotle, Basil considered a number of possible answers: the earth rests on air, or on water, or on something heavy. Rejecting these options – for example, if a heavier object supported the earth, one would then have to ask what held up the heavier object, and so on – Basil concluded that the earth has no reason to move because it lies in the middle of everything.[4] He never tired of emphasizing the marvelous design that God embedded in nature.

Basil frequently mixed his descriptions of natural phenomena and design, especially of the behavior of animals and plants, with morality. As he put it, "Everything in existence is the work of Providence, and nothing is bereft of the care owed to it. If you observe carefully the members even of the animals, you will find that the Creator has added nothing superfluous, and that He has not omitted anything necessary."[5] He drew lessons from the migration of fish, the stealth of the octopus, the function of the elephant's trunk, the behavior of dogs tracking wild animals, and the existence of both poisonous and edible plants. All play their designated role in nature, even poisonous plants, for, as Basil argued, "there is no one plant without worth, not one without use. Either it provides food for some animal, or has been sought out for us by the medical profession for the relief of certain diseases."[6] Thus did Basil respond to those who wondered why God would create poisonous plants capable of killing humans.

Basil's ideas were enormously influential in the western and eastern parts of the Roman Empire. In the West, Saint Ambrose (ca. 339–397), who possessed a sufficient knowledge of Greek to make use of Basil's homilies in his own Latin hexaemeral treatise, was instrumental in introducing Basil's ideas into the Latin language. (Basil's treatise was translated into Latin in the fifth century and was known directly in the Middle Ages.) It was Saint Augustine, however, who composed the most formidable and influential early Latin commentary on the creation account in Genesis. Not only was his much lengthier than those by Basil and Ambrose (he was familiar with Ambrose's), but it was also much more informative and philosophical. It had a considerable impact in the late Middle Ages, especially on the theological students who were required to write commentaries on Peter Lombard's *Sentences*, the second book of which was concerned with the creation and about which we shall say more later.

Basil also had an impact on Greek writers in the East, especially on John Philoponus, a Christian commentator on Aristotle of the sixth century. Philoponus's hexaemeral treatise was incomparably more sophisticated than Basil's. In defending the Mosaic account in Genesis against the traditional pagan Greek description of the physical world, Philoponus found it necessary to discuss numerous scientific claims and arguments. When his treatise became available in Western Europe in the sixteenth century, it made a significant impact.

Although these early Christian authors subordinated science and the study of nature to the needs of religion, they often indicated an interest in nature, as did Basil, that transcended the mere ancillary status that the study of nature was customarily accorded. The attitude of theologians toward natural philosophy during the late Middle Ages is eloquent testimony that invocation of the handmaiden theory eventually became little more than formulaic.

CHRISTIANITY AND GRECO-ROMAN CULTURE

Greco-Roman culture and learning was sometimes viewed with suspicion, but it was not considered an enemy and its potential utility was recognized early on. Indeed, it may have received unintended support from the Christian attitude toward the state. Because they believed that the kingdom of heaven was imminent, early Christians paid relatively little heed to the world around them. They sought generally to meet their obligations to the state insofar as these did not violate their religious scruples. Nowhere is this better exemplified than in Jesus' reply to the Pharisees who sought to trap him by asking whether they should pay taxes to the Roman emperor. Their question presented Jesus with a dilemma: if he urged them not to pay taxes, he would be guilty of treason to the state; but if he urged them to pay, he would antagonize Jewish nationalists. Jesus' reply was momentous when he urged that they "Render therefore unto Caesar the things which are Caesar's; and unto God the things that are God's" (Matt. 22.21). Thus did Jesus acknowledge the state and implicitly urge his followers to be good citizens.

From the outset, Christians recognized the state as distinct from the church, although, as the Roman Catholic Church became more centralized, various popes sought to dominate the multiplicity of states in Europe. They based their arguments on the conviction that, by the nature of things, the priesthood had to be closer to God than did secular rulers. In a letter to Anastasius, the Eastern emperor, Pope Gelasius (492–496) declared that "there are . . . two by whom principally this world is ruled: the sacred authority of the pontiffs and the royal power. Of these the importance of the priests is so much the greater, as even for Kings of men they will have to give an account in the divine judgment."[7] The later pretensions of the papacy were based on this notion. The pope claimed supremacy over emperors and kings, as when Innocent III (1198–1216) declared that "The Lord Jesus Christ has set up one ruler over all things as his universal vicar, and as all things in heaven, earth and hell bow the knee to Christ, so should all obey Christ's vicar, that there be one flock and one shepherd" and again when he proclaimed that "The *sacerdotium* [priestly power] is the sun, the *regnum* [royal power] is the moon. Kings rule over their respective kingdoms, but Peter rules over the whole earth. The *sacerdotium* came by divine creation, the *regnum* by man's cunning."[8]

A counterattack by the secular power, whether the Holy Roman Emperor or one or another of the kings of Europe, when it came, usually involved an invocation of Christ's statement that one ought to give to Caesar, or to the state, what is Caesar's, and give to God what is God's; or that Christ sat on David's throne as king and not on Aaron's throne as high priest; or that Christ would eventually rule the human race as king, not priest.[9]

From the fifth century through the late Middle Ages, the struggle for supremacy between the papacy and the numerous secular rulers with which it had to contend was ongoing. The power of the papacy reached its high point during the early thirteenth century with the pontificate of Innocent III, after which it declined, largely because secular rulers became so wealthy and powerful that they could no longer be controlled from Rome.

Significant here, however, is not which of these two contending powers was dominant at any time, but rather that each acknowledged the independence of the other. They regarded themselves as two swords, although, all too often, the swords were pointed at each other. Even when the Church asserted supremacy over the state, however, it never attempted to establish a theocracy by appointing bishops and priests as secular rulers. The tradition of the Roman state within which Christianity developed and the absence of explicit biblical support for a theocratic state were powerful constraints on unbridled and grandiose papal ambitions and, above all, made the imposition of a theocratic state unlikely. Although church and state were not as rigidly separated in the Middle Ages as they are today in the United States and Western Europe, and the two often interacted, even blatantly intervening in each other's affairs, they were, nonetheless, independent entities. Pope Gelasius's words cited earlier – "there are . . . two by whom principally this world is ruled: the sacred authority of the pontiffs and the royal power" – bear witness to the separation.

Why are the relationships between early Christianity and Greek science and philosophy on the one hand, and between the Christian church and the secular state on the other hand, relevant to the history of science? Because, as we shall see, the separation of church and state, at least in principle, and, more significantly, the Christian accommodation with Greek science and philosophy, were instrumental conditions that facilitated the widespread, intensive study of natural philosophy during the late Middle Ages. As a consequence of the emergence of natural philosophy within the unique university system of the Latin Middle Ages, the revolutionary developments in science of the sixteenth and seventeenth centuries were made possible. We may better appreciate the force of these claims by a comparison of Western European developments with developments in two major contemporary civilizations, Islam and the Byzantine Empire. The differences are striking and will be described in the final chapter.

THE STATE OF SCIENCE AND NATURAL PHILOSOPHY DURING THE FIRST SIX CENTURIES OF CHRISTIANITY

To comprehend the state of science that obtained by the beginning of the seventh century, it is essential to sketch the basic events that transformed the Roman Empire. During its first two centuries, from the reign of Caesar Augustus to the death of Marcus Aurelius, the Romans controlled a vast empire in which two languages were dominant. In the west, not surprisingly, the Romans succeeded in imposing a basic Roman culture in which Latin was the common means of communication, overlaying a multiplicity of native languages in the regions of Italy, Gaul, Spain, Britain, and North Africa. In the eastern part of the Roman Empire, which to a considerable extent coincided with the old Hellenistic world left in the wake of the conquests of Alexander the Great (that is, Greece, Asia Minor, Syria, Persia, Palestine, and Egypt), Greek was the common language. Beginning with the emperor Diocletian (284–305), the Roman Empire was split administratively into eastern and western parts, largely reflecting the linguistic split into Greek- and Latin-speaking regions. Diocletian chose a colleague, Maximianus, to rule in the West, while he governed in the East, establishing a new capital at Nicomedia. In 330, Constantine established yet another new capital in the East, Constantinople, locating it at the site of an old Greek colony, Byzantium, a name that would eventually stand for the empire itself. For a brief period, between 394 and 395, Theodosius the Great reunited the empire, ruling as sole emperor. Following his death in 395, however, the empire was again ruled by two independent, self-proclaimed emperors, one in the East and one in the West. The line of emperors in the West ended in 476, when Romulus Augustulus was deposed. But even with German states functioning in the Western empire after 476, the Roman Empire was still viewed as intact, and German rulers often acknowledged the empire by either taking or accepting the honored title of consul. This state of affairs continued until Charlemagne was crowned "Emperor of the Romans" by Pope Leo III on December 25, 800, thus beginning the long history of the Holy Roman Empire in Western Europe. By the time of Charlemagne's coronation, Western Europe had long ceased to be a de facto part of the Roman Empire. In the East, however, Roman emperors reigned continuously from the time of Constantine's foundation of Constantinople until the city fell to the Turks in 1453, more than one thousand years later. Thus did the Roman Empire fall for the final time.

Although Latin was the language of the Romans, and Roman military might had created a vast empire, the language of learning in the Roman Empire was Greek. In this sense, Athens conquered Rome. Latin-speaking Romans with intellectual pretensions, never a large group, usually learned Greek, and some went to Greece for their education.

How did science fare within the Roman Empire? Despite much political and military turmoil, the multiplication of mystery religions, and an emphasis on the occult, some of the greatest scientific works of the ancient world were written in this period (as always in the Greek language and in the eastern half of the empire). A few of these works exerted a profound influence on the later course of medieval science and well beyond into the Renaissance.

The first century A.D. saw the significant works of Hero of Alexandria (who wrote on pneumatics, mechanics, optics, and mathematics), Nicomachus (on Pythagorean arithmetic), and Theodosius and Menelaus (who both wrote on spherical geometry; Menelaus's *Spherics* is especially important for the treatment of spherical triangles and trigonometry). The greatest works in astronomy and medicine were written in the second century. Claudius Ptolemy wrote the *Mathematical Syntaxis*, or *Almagest*, as it was called by the Arabs, the greatest treatise in the history of astronomy until the time of Copernicus in the sixteenth century. Ptolemy's scientific genius was not confined to astronomy. He also wrote technical works in optics, geography, and stereographic projection, and he even produced the greatest of all astrological works, the *Tetrabiblos* (known in Latin as the *Quadripartitum*, the four-parted work). In the medical and biological sciences, Galen of Pergamum produced about one hundred fifty works embracing both theory and practice, which formed the basis of medical theory and study until the sixteenth and seventeenth centuries. Even in the third century significant contributions were made in mathematics by Diophantus in algebra and later by Pappus, who not only wrote commentaries on the great mathematical works of Greek antiquity but also, in his *Mathematical Collection*, showed originality and understanding of a high order.

The Greek world of late antiquity also contributed powerfully to natural philosophy, largely by way of commentaries on the works of Aristotle. Because Aristotelian natural philosophy plays a central role in this study, and because the Greek commentaries on Aristotle's works in late antiquity were of particular importance for the subsequent history of science, a brief description of the late Greek commentators will be given in the next chapter.

The achievements of the first six centuries of the Christian era were typical of the manner in which Greek science and natural philosophy had developed and advanced. Always the product of a small number of gifted scholars concentrated in a few centers, Greek science was a fragile enterprise, able to advance and preserve itself just so long as the intellectual environment was favorable, or at least not overtly antagonistic. Greek science at its traditional best in the Roman Empire was but a continuation of the progress already made in the physical and biological sciences of classical Greece and the Hellenistic world, when the works of Plato, Aristotle, Hippocrates, Eudoxus, Euclid, Archimedes, Appollonius of Perga, Hipparchus, Theophrastus, Herophilus, and Erastistratus established the highest levels of achievement.

As in our own day, however, there existed in antiquity an audience of educated individuals interested in the physical world but with little inclination or ability to tackle forbidding scientific treatises of a theoretical and abstract nature. To meet the needs of this group, scientific popularizers simplified and rendered palatable conclusions from the exact sciences and natural philosophy, which were then incorporated into handbooks and manuals. Greek authors began the process of popularization in the Hellenistic period. Not surprisingly, some of these treatises were filled with contradictory information. Readers who were astute enough to detect the inconsistencies were left to reconcile them as best they could.

Greeks who were instrumental in shaping the handbook tradition were the polymath Eratosthenes of Cyrene (ca. 275–194 B.C.), who supplied much geographical knowledge to the tradition; Crates of Mallos (fl. 160 B.C.); and especially Posidonius (ca. 135–51 B.C.), whose numerous works have not survived, but whose opinions on meteorology, geography, astronomy, and other sciences were absorbed into later handbooks to become permanent fixtures in the tradition. Continuing in the manner of Posidonius were other Greek authors, such as Geminus (ca. 70 B.C.); Cleomedes (first or second century A.D.), who wrote the astronomical and cosmological work *On the Cyclic Motions of the Celestial Bodies*; and Theon of Smyrna (first half of the second century A.D.), who wrote the *Manual of Mathematical Knowledge Useful for an Understanding of Plato* in which the whole universe is discussed, just as it is in Plato's *Timaeus*. Theon drew upon astronomy and cosmology as well as Pythagorean arithmetic and mathematics.

Commentaries on Plato's *Timaeus* constituted a significant part of the handbook tradition from the Hellenistic period to the early Middle Ages. Because the *Timaeus* was a scientific treatise concerned not only with the cosmos but also with the biological status of the human species, it was an admirable vehicle for the handbook tradition, and physical and biological themes could be appropriately included.

Following their conquest of Greece, Roman gentlemen were brought into contact with Greek culture during the second and first centuries B.C. By this time, the Greek handbook tradition was established and its treatises were admirably adapted to cater to Roman cultural interests. For although the Romans were awed by Greek intellectual accomplishments, they had little interest in theoretical and abstract science. When fashion dictated that cultured Romans become acquainted with the results of Greek science, the handbook method was there to meet the need. Romans who knew Greek consulted the Greek handbooks directly, but the great majority of Romans absorbed their knowledge through Latin translations or summaries. Soon, Latin authors began compiling their own handbooks on science.

Although the Latin encyclopedic tradition actually began in the first century B.C. with Marcus Terrentius Varro (116–27 B.C.), its two most significant early representatives were Seneca (d. A.D. 68) and Pliny the Elder (A.D. 23/24–79). In *Natural Questions*, Seneca concerned himself largely with geography and meteorological phenomena (for example, rainbows, halos, meteors, thunder, and lightning), after the manner of Aristotle's *Meteorology*. He drew heavily upon Aristotle, Posidonius, perhaps his major authority, Theophrastus, and other Greek sources. Because Seneca frequently drew morals from natural phenomena, his book was popular with Christians. He also transmitted to the Middle Ages an estimate of the size of the earth that was small enough to encourage men like Columbus and others to think that the oceans were sufficiently narrow to be readily navigable. Seneca also struck an optimistic note on the progress of science and knowledge when he predicted that continuous research would reveal nature's secrets.

Pliny's *Natural History* in thirty-seven books was a remarkable scissors-and-paste collection of enormous scope and detail. By his own estimate, he examined about two thousand volumes drawn from 100 authors. In Book I, Pliny presents a detailed outline of the topics and a full list of the authorities used for each of the thirty-six volumes that follow. Thus did he honor his predecessors. A total of 473 authors are listed, of whom presumably the 100 mentioned in his estimate were primary and some of the others were either known through intermediaries or perhaps used cursorily for isolated facts. Book II is devoted to cosmography; Books III to VI to regional geography; and Book VII to human generation, life, and death. Books VIII to XXXII are concerned with zoology and botany, including fabulous animals and the curative powers associated with animals and plants, and Books XXXIII to XXXVII consider mineralogy. As an indefatigable compiler, Pliny emphasized the curious and the odd in natural phenomena. Although confusions, inconsistencies, and misunderstandings abound in his work, the weakest sections are those that attempt to explain Greek theoretical science, which Pliny scarcely comprehended.

If Pliny's work was confused and frequently inconsistent, it was at least the product of great diligence coupled with an honest respect for the sources that provided the grist for his insatiable mill. Few of his successors shared his finer instincts. Although Pliny acknowledged many, if not most, of his sources, he would not have been thought immoral had he not done so. Plagiarism was not regarded as an intellectual crime. It would be inappropriate to apply our modern standards on plagiarism to the ancient and medieval worlds when incorporating passages from someone else's treatise was not considered reprehensible, nor was it censured by custom or practice. In the compilations of Pliny's late ancient and early medieval successors, passages and sections were often extracted from the works of others without acknowledgment. Thus Solinus, who lived in the third or fourth century A.D., compiled the encyclopedic *Collection of Remarkable Facts*, about which the most remarkable fact is that Solinus lifted most of it from Pliny. Solinus's treatise was so thoroughly raided in its turn that modern scholars are frequently unable to determine whether Pliny or Solinus was the source of this or that later opinion. Encyclopedic authors looked upon available handbooks as storehouses of information in the public domain that could be extracted, embellished, and rearranged to suit their purposes. The final products were then paraded as learned treatises drawn directly from the original sources. The scientific works and opinions of the likes of Plato, Aristotle, Archimedes, Euclid, Theophrastus, and others were cited repeatedly in the handbooks, as if the compilers had direct knowledge of them. It is all too apparent, however, that these encyclopedists had no direct acquaintance with the great scientific authors of the past and were but repeating – and frequently distorting – what earlier compilers had already repeated and distorted from their predecessors.

Between the fourth and eighth centuries, encyclopedic authors produced a series of Latin works that were to have significant influence throughout the Middle Ages, especially prior to 1200. Among this group, the most important were Chalcidius, Macrobius, Martianus Capella, Boethius, Cassiodorus, Isidore of Seville, and Venerable Bede. Chalcidius (fl. ca. fourth century A.D.) translated most of Plato's *Timaeus* into Latin and added a commentary whose astronomical portions he drew from Theon of Smyrna's *Manual*, mentioned earlier. Macrobius (fl. 400 A.D.), a Neoplatonist, incorporated encyclopedic learning into a commentary on Cicero's *Dream of Scipio*, which is actually Book VI of Cicero's *Republic*. Martianus Capella (fl. 410–439) wrote the popular *Marriage of Philology and Mercury*, an ornate, florid account of the seven liberal arts and a pale reflection of classical learning and wisdom.

Ancius Manlius Severinus Boethius (ca. 480–524) was one of the best of the Latin encyclopedists and also an unusual one because he knew Greek, although the extent of his knowledge is uncertain. Boethius wrote on the "quadrivium" (a term he may have introduced for the four mathematical sciences of the seven liberal arts), of which only his treatises on music and Pythagorean arithmetic survive, the latter in the form of a free translation of Nicomachus's *Introduction to Arithmetic,* originally composed in Greek. To these Boethius added his translations of some of Aristotle's logical treatises, perhaps Euclid's *Elements,* and unspecified works of Archimedes that have not survived. His commentaries on certain of the philosophical treatises that he translated and his most famous work, *On the Consolation of Philosophy,* written in prison while he awaited execution, were very influential. Cassiodorus (ca. 488–575) included sections on the seven liberal arts in his *Introduction to Divine and Human Readings* and was reasonably scrupulous about citing his authorities. Isidore of Seville (ca. 560–636), in addition to writing a treatise titled *On the Nature of Things,* compiled a vast encyclopedia called *The Etymologies,* in which he discussed the seven liberal arts, medicine, zoology, the mechanical arts, metallurgy, and other topics. Finally, there is Venerable Bede (ca. 673–735), perhaps the most intelligent of the Latin encyclopedists. In addition to a conventional encyclopedia, *On the Nature of Things,* Bede wrote two treatises, *On the Division of Time* and *On the Reckoning of Time,* which were concerned with calendar reckoning and in which he discussed such topics as chronology, astronomy, calendrical computations, Easter tables, and the tides. Although he borrowed heavily from his predecessors, especially Isidore, Bede was capable of adding intelligently to his meager inheritance. For example, he formulated the concept of the "establishment of the port" and recorded that the tides recur at approximately the same time at a particular place along the coast, although the times of occurrence vary from place to place.

THE SEVEN LIBERAL ARTS

In a few instances, I have mentioned the seven liberal arts, and it will be useful to describe them more fully. They embraced both verbal and mathematical disciplines. The former, known as the "trivium," included grammar, rhetoric, and logic (or dialectic), whereas the latter, the "quadrivium," encompassed the four disciplines of arithmetic, geometry, astronomy, and music. All of these disciplines took form in classical Greece during the fifth and fourth centuries B.C., when they were first conceived as liberal arts suitable for teaching to free young men. The number of disciplines varied, however, and did not assume the canonical number of seven until the time of the Latin encyclopedists, who also coined the terms "trivium" and "quadrivium." The Latin encyclopedists shaped the seven liberal arts into the form they would have in the later Middle Ages. Martianus Capella's *Marriage of Philology and Mercury* was perhaps the quintessential Latin treatise that shaped the seven liberal arts. The setting of the book is the marriage of Mercury and Philology, where each of the seven arts is represented by a bridesmaid, who describes the art she represents. Others also wrote on the seven liberal arts, including Saint Augustine, Boethius, Cassiodorus, and Isidore of Seville. It was Cassiodorus who urged that the seven liberal arts be incorporated into a Christian education. By the end of the seventh century, the seven liberal arts were considered to be the basis of a proper education.

If there was such a thing as a core of scientific learning, it would be embedded in the quadrivium. Indeed, the four mathematical sciences that comprised it (arithmetic, geometry, astronomy, and music) were given their final condensed form by the Latin encyclopedists. Of the various accounts that discussed the quadrivium, the most popular and representative was Isidore of Seville's lengthy *Etymologies.* As the title suggests, Isidore was often concerned with etymological derivations of key terms, believing that knowledge of the origin of a term conveys an insight into the essence and structure of the thing it represents.

Isidore called attention to the importance of arithmetic for a proper understanding of the mysteries of Holy Scripture. For the arithmetic itself, he drew heavily upon Cassiodorus, who had, in turn, excerpted from the lengthy Boethian translation of Nicomachus's *Introduction to Arithmetic.* Isidore considered the division of numbers into even and odd and distinguished various subdivisions within each category. He enunciated a mélange of Pythagorean definitions, including those for excessive, defective, and perfect numbers (that is, where the sum of the factors of a number respectively exceeds, is less than, and equals the number itself), as well as for discrete, continuous, lineal, plane, circular, spherical, and cube numbers. If we add to these the definitions of five types of ratio distinguished by Nicomachus, then we have virtually the whole of Isidore's arithmetic. Faced with an unrelated collection of inept definitions, supplemented by a few trivial examples, the reader of Isidore's section on arithmetic could have used little of it. A comparison with the arithmetic books of Euclid's *Elements* (Books VII to IX) illustrates the depths to which arithmetic had fallen.

Isidore has even less to say about geometry. He begins with a strange fourfold division into plane figures, numerical magnitude, rational magnitude, and solid figures, and he concludes with definitions of "point," "line," "circle," "cube," "cone," "sphere," "quadrilateral," and a few others. Here we find "cube" defined as "a proper solid figure which is contained by length, breadth, and thickness," a definition applicable to any other solid (Euclid defined "cube" as a "solid figure contained by six equal squares"). A quadrilateral figure is "a square in a plane which consists of four straight lines," thus equating all four-sided figures with squares![10]

Isidore's longest section within the quadrivium is devoted to astronomy (the music section, like that on geometry, consists of a brief sequence of definitions). In a nontechnical description, Isidore considered the difference between astronomy and astrology, the general structure of the universe, the sun, the moon, the planets, fixed stars, and comets. We learn that the sun, which is made of fire, is larger than the earth and the moon; that the earth is larger than the moon; that, in addition to a daily motion, the sun has a motion of its own and that it sets in different places; that the moon receives its light from the sun and suffers eclipse when the earth's shadow is interposed between it and the sun; that the planets have a motion of their own; and that the stars, fixed and motionless in the heavens, are carried around by a celestial sphere, although the stars themselves are ranged at varying distances from the earth, an inference drawn from the observed unequal brightnesses of stars. Isidore believed that some of the more remote and smaller stars were actually larger than the bright stars that humans observe, their apparent smallness being merely a consequence of distance. It is unlikely that Isidore was aware that an unimaginably thick and transparent sphere would be required to accommodate fixed stars varying in size and distance and distributed under the conditions he described. Comprised, for the most part, of elementary and sketchy details, Isidore's astronomical discussion nevertheless represents his best effort among the subjects of the quadrivium.

The extent to which the quadrivial sciences were actually taught is problematic. It is not likely that they were taught in more than a cursory fashion. Few knew the four subject areas well enough to teach them, although Boethius had written treatises on arithmetic and music and perhaps also on astronomy and geometry. Nevertheless, the seven liberal arts served as an ideal core of education in the cathedral schools of the eleventh and twelfth centuries, and their study intensified in the twelfth century, even as new intellectual riches began to enter Europe from the Islamic world. With the emergence of universities in the late twelfth and thirteenth centuries, the liberal arts were greatly expanded as these growing institutions absorbed the new learning. Ironically, they were no longer taught as the seven liberal arts but rather as independent subjects in a broad-ranging curriculum. Indeed, the new emphasis at the universities was on natural philosophy and theology to which the liberal arts, insofar as they existed at all, were preparatory subjects.

The Latin encyclopedists supplied the early Middle Ages with most of what its scholars would know of science and natural philosophy. Their information was largely derived from the Greek and Latin handbook traditions. Too often, they failed to comprehend the material they read; nonetheless, they copied it, or paraphrased it, in their own treatises. Despite their failings, the encyclopedists performed a vital service. Without their contributions, even the meager knowledge of the world that they provided would have been absent.

The encyclopedists provided late ancient and early medieval society with what has been characterized as "popular" science. Today, we also have popular science, ranging in quality from poor to excellent. A critical difference between our society and that of the Roman West is that the experimental and theoretical science on which our popular science is based was absent from Roman science during late antiquity and the early Middle Ages. Popular science in the Roman West was nearly coextensive with the whole of science. It was embodied in the quadrivial subjects described by the encyclopedists, who deserve our gratitude for their efforts to preserve the remnants of ancient science. There is no denying, however, that a scientific dark age had descended upon Western Europe.

4

What the Middle Ages inherited from Aristotle

Aristotle's natural books formed the basis of natural philosophy in the universities, and the way in which medieval scholars understood the structure and operation of the cosmos must be sought in those books. By his use of assumptions, demonstrated principles, and seemingly self-evident principles, Aristotle imposed a strong sense of order and coherence on an otherwise bewildering world. Aristotle's medieval disciples, who formed the class of natural philosophers during the late Middle Ages, would eventually extend Aristotle's principles to activities and problems beyond anything that the philosopher himself had considered.

Aristotle was convinced that the world he sought to understand was eternal, without beginning or end. He regarded the eternity of the world as far less problematic than any assumption of a cosmic beginning that also implied a future end to the world. It was better to postulate eternity than be forced into an explanation that required an infinite regress of causal beginnings. The idea that matter could have a beginning seemed impossible to the ancient Greeks, for if one were to arrive at some alleged pristine matter, it would inevitably lead to the question of what caused it, and so on. Without a beginning, however, the world could not have been created, and thus Aristotle's ideas about the eternity of the world set him in opposition to the theologians of the great monotheistic religions of Judaism, Christianity, and Islam. Of all the issues that involved natural philosophy and theology during the thirteenth century in Western Europe, theologians regarded the eternity of the world as the most difficult and threatening for the faith (see chapter 5).

Still, if Aristotle's world was eternal and therefore suspect, his insistence on its uniqueness placed him squarely in agreement with the sacred scriptures of the three great religions. He regarded our world as unique, a large finite sphere beyond which nothing could exist. All existent matter is contained in our world, with none left over. Without body, "neither place, nor void, nor time" could exist beyond the world, because the definitions of "place," "void," and "time" all depended on the existence of body. For Aristotle the proper place of a body was always the innermost surface of another immediately surrounding body that was in direct contact with the contained body. Thus a place is defined as something in which body must be present. Without the existence of a body beyond our world, no place could exist (for more on place, see later in this chapter). Similarly, a void is something in which the existence of a body is possible, though not actual. Therefore, if no body is possible, no vacuum is possible. Finally, time is the measure of motion. Without body there can be no motion and, therefore, no time. Aristotle concluded that all existence lay within our cosmos, and nothing beyond. The "nothing" in this sense is not to be construed as a vacuum, but is best characterized as a total privation of being.

Perhaps the most momentous decision that Aristotle made about the eternal, physical world was to divide it into two radically different parts, the terrestrial, which extended from the center of the earth to the lunar sphere, and the celestial, which embraced everything from the moon to the fixed stars. In the terrestrial region, observation and experience made it obvious that change was incessant, whereas in the celestial region change was virtually nonexistent. Astronomical observations inherited from the past convinced Aristotle that no changes had ever been detected in the heavens (*De caelo* 1.3.270b.13–17), from which he inferred that changes did not – and could not – occur there. To understand Aristotle's world better, it is advantageous to describe first the terrestrial region of change, which, in turn, will make the unchanging properties and attributes of the celestial region more comprehensible.

THE TERRESTRIAL REGION: REALM OF INCESSANT CHANGE

Much of Aristotle's natural philosophy is an attempt to identify and explicate the principles of change in the terrestrial region, principles that shaped medieval interpretations of the processes that make the world what it is. Although we live in a world that had no beginning, Aristotle nonetheless explains how the development of matter is to be imagined and how it is differentiated into four basic elements – earth, water, air, and fire – that form the building blocks of all material bodies in the terrestrial region. The underlying basis of all material bodies is prime matter, which, although real, has no independent existence. Aristotle simply infers its reality because it was essential to assume the existence of some kind of substratum in which qualities and forms could inhere and produce sensible matter. Prime matter has no properties of its own, but is always associated with qualities that inhere in it and define it.

Which properties or qualities would raise prime matter to a higher existent level, say to the level of an element? After eliminating a number of possibilities, Aristotle argues that two pairs of contrary, or opposite, qualities could achieve this effect: hot and cold, and dry and moist. Because nothing could be simultaneously hot and cold, or dry and moist, no single pair of opposite qualities could inhere in prime matter at the same time. Non-opposite combinations, however, are possible and can produce elements. If the qualities coldness and dryness inhered in prime matter, they would produce the element earth; coldness and wetness would produce water; hotness and wetness air; and hotness and dryness fire. Thus were the four elements derived. The perceptible bodies of the terrestrial region were, however, not pure elements, but mixtures, or compounds, of two or more of them, usually called "mixed" bodies in the Middle Ages.

In Aristotle's natural philosophy, or physics, every body is a composite of matter and form, where the matter serves as a substratum in which the form inheres. The form of a thing, or a body, is its essential defining characteristics, the properties that make it what it is. Nature in the terrestrial realm is nothing more than a collective term for the totality of existent bodies, each comprised of matter and form. Every such body belongs to its own species and possesses the properties and characteristics – that is, the form – of its species. If unimpeded, it will act in conformity with those properties. Aristotle thus attributed to the bodies of the world a power to act in accordance with their natural capabilities. In this way, he allowed for secondary causation, where bodies were capable of acting on other bodies, that is, able to cause effects in other bodies. Aristotle believed that each effect was produced by four causes acting simultaneously, namely a material cause, or the thing out of which something is made; a formal cause, or the basic structure to be imposed on something; an efficient cause, or the agent of an action; and the final cause, or the purpose for which the action is undertaken. The causes that produce a stone not only make it heavy, but, if the stone is otherwise unimpeded, that heaviness confers upon it the capacity to fall naturally toward the center of the earth with a rectilinear motion. Similarly, the agents that produce fire confer lightness upon it and therefore the capability of rising naturally upward, whenever it is unhindered.

Aristotle was also concerned about the kinds of changes that the four causes could produce, distinguishing four kinds: (1) substantial change, where one form supplants another in the underlying matter, as when fire reduces a log to ash; (2) qualitative change, as when the color of a leaf is altered from green to brown in the same underlying matter; (3) change of quantity, as when a body grows or diminishes while otherwise retaining its identity; and, finally, (4) change of place, when a body suffers change as it moves from one place to another.

Of these four types of change, only the first and fourth require explanation. Substantial change is the most basic form of change, involving generation and corruption. For Aristotle every substantial change implied that something had come into existence from the passing away of something else. This coming-to-be and passing-away of things was the basis of all change in the terrestrial region. It occurred in all substances composed of matter and form, which in the terrestrial region included all things. Forms, or qualities, were potentially replaceable by other forms that were their contraries. When this occurred, one substance was changed into another. For example, fire, which possesses the primary qualities of hotness and dryness, is changed into earth, which possesses the primary qualities of dryness and coldness, when the hotness in fire is replaced by coldness, its contrary quality, or form. While one form is actualized in matter, its contrary is said to be in privation but potentially capable of replacing it. Eventually, each potential form or quality must actually become what it is capable of becoming; otherwise a form would remain unactualized, and nature would have produced it in vain. While one of a pair of contrary forms is actualized in matter, its contrary is absent and in privation, because two contrary forms cannot exist simultaneously in the same body. Virtually all change, that is, generation and corruption, involves the possession of one, and the exclusion of another, of a pair of contrary forms or qualities.

The last of the four changes, change of place, represents what we ordinarily think of as motion, the removal of a body from one location to another. Aristotle's doctrine of place may be viewed in two ways. In its broadest signification, it concerns the structure of the sublunar world; and in the narrowest and most restrictive sense, it involves the specific place of a single body. The broad sense of place is really the doctrine of natural place, in which Aristotle conceived of the part of the world below the moon as a structured region divided into four concentric areas, each the natural place of an element, toward which that element would naturally move if unimpeded. Thus the outermost concentric ring, located just below the concave surface of the lunar sphere, is the natural place of fire; the next concentric ring is the place of air, toward which air rises if in the regions below, or toward which it would fall if, for some reason, it was located in the region of fire; below air is the ring of water; and below that the sphere of our earth, the center of which coincides with the geometric center of the universe.

The earth's sphericity was a basic truth of Aristotle's system of the world. As observational evidence of its sphericity, Aristotle pointed to the curved lines on the Moon's surface during a lunar eclipse, inferring rightly that these were cast by the shadow of a spherical earth interposed between the Sun and the Moon. He also noted that as one changed position on the earth's surface, different stellar configurations came into view, indicating that the earth possessed a spherical surface. The sphericity of the earth seemed further confirmed by the way bodies were observed to fall to the earth's surface in nonparallel lines that met at its center. If all earthy bodies fell in this manner, they would cluster around the center of the world and form naturally into a sphere. So reasonable were Aristotle's arguments that a spherical earth was readily accepted.

What, however, about the place of any particular body? Aristotle's doctrine of place is based upon a fundamental conviction that the world is a material plenum in which the existence of void space is impossible. From this it followed that the place of any individual thing in the sublunar region consisted of the matter that surrounded it; or, as Aristotle described it, the place of a thing is "the boundary of the containing body at which it is in contact with the contained body."[1] The boundary, or innermost surface of the container, was also required to be motionless, a qualification that posed serious problems in the history of Aristotle's doctrine of place. It frequently happened that where the condition of contact was met, that of immobility was not, and vice versa. Nevertheless, when a body met these stringent conditions, it was presumed to be in its "proper place," that is, in a place that it alone occupied. Places that included more than one distinct body were characterized as "common places." Because Aristotle assumed that every body was somewhere, and therefore necessarily in a place, he was inevitably led to ask whether the outermost surface of the outermost sphere that contained the world was itself in a place, a question tantamount to asking whether the world itself is in a place. Convinced that bodies did not exist beyond the world, Aristotle argued that if no material body, and therefore no surface of a body, could surround our world, no body could function as its place. Paradoxically, although every body in the world is in a place, the last sphere, or the world itself, is not directly in a place. Apparently uneasy with this consequence of his doctrine of place, and perhaps fearful of being perceived as inconsistent, Aristotle found a kind of place for the last sphere by arguing that the last sphere is in a place indirectly by means of its parts, because "on the orb one part contains another."[2] Many of Aristotle's commentators rejected his cryptic attempt to find a place for the last sphere. And those who did not were often led into bizarre explanations to defend the master, as when Averroes argued that the last sphere is in a place accidentally (*per accidens*) because its center, the earth, is in a place essentially (*per se*). Thomas Aquinas thought it "ridiculous to say that the last sphere is in place accidentally [simply] because the center is in a place."[3] How could a container be in place by virtue of the thing it contains?

Motion in Aristotle's physics

The motion of bodies from place to place was a problem that Aristotle frequently considered, although nowhere in his extant works is there a systematic and comprehensive treatment of it. The account that follows is based upon discussions scattered through a number of his works, especially the *Physics* and *On the Heavens*.

In a sublunar world that had no empty spaces and was a material plenum, motion, or local motion, as it was sometimes called, had to be from one place in that plenum to another. Aristotle distinguished two kinds of motion: natural and violent (or unnatural), a division that probably originated in gross observation. The division of local motion into natural and violent and the cluster of concepts, arguments, and physical assumptions associated with these two contrary motions formed the core of Aristotle's sublunar physics.

Natural motion of sublunar bodies. Aristotle's concept of natural motion was dependent on obvious properties he observed in the four elements – earth, water, air, and fire – that formed the material basis of all terrestrial bodies. When falling from heights, some bodies, like stones, were seen to move in straight lines toward the center of the earth. Other bodies, such as fire or smoke, always seemed to rise toward the lunar sphere and away from the earth's center. Because the class of bodies that fell naturally toward the center of the earth was, on the basis of experience, observed to be heavier than the classes of bodies that rose, Aristotle concluded that, when unimpeded, a heavy, or earthy, body moved naturally downward in a straight line toward the center of the earth. Thus the center of the earth – or more precisely, the geometric center of the universe – was the natural place of all heavy bodies. Conversely, light bodies moved naturally upward in a straight line toward the lunar sphere, which was conceived as their natural place. Aristotle described these natural up-and-down motions as accelerated.

Let us now apply these generalizations specifically to the four elements. Whenever an elemental body, composed primarily of earth, was above its own natural place – whether that place was in water, air, or the fiery region above the air – it was deemed absolutely heavy because, if unimpeded, it would fall toward toward the earth's center. Fire was regarded as absolutely light; if unimpeded, fire would always rise upward from the regions below toward its natural place above air, and below the lunar sphere. To emphasize fire's absolute lightness, Aristotle declared it "a palpable fact" that "the greater the quantity [of fire], the lighter the mass is and the quicker its upward movement."[4] By assuming that the greater the quantity of fire, the lighter it becomes and the faster it rises, Aristotle seems to have dissociated absolute lightness from the concept of weight, a concept that is unintelligible in this context. As for water and air, Aristotle regarded them as intermediate elements possessing only relative heaviness and lightness. When below its natural place somewhere within the earth, water would naturally rise; but when above its natural place, in air or fire, it would fall. Air, however, would fall when in the natural place of fire, but rise when in the natural place of earth or water.

Thus far we have described the idealized, natural behavior of each of the four elements. But the elements did not exist in a naturally pristine state. In the real world, bodies were actually compounds made up of varying proportions of all four elements. Bodies that fell naturally toward the earth's center did so because their predominant element was heavy (the heavier the body, the greater its speed of descent); those that rose naturally upward did so because they were dominated by a light element (the greater the quantity of air or fire in an airy or fiery body, the greater would be its speed of ascent).

Three pairs of opposites played a significant role in Aristotle's interpretation of the structure of the terrestrial, or sublunar, world. They may be schematized as follows:

1. Concave surface of lunar sphere	Geometric center of universe (or center of the earth)
2. Up	Down
3. Absolute lightness (fire)	Absolute heaviness (earth)

These opposites served as virtual boundary conditions for Aristotle's scattered account of the motion of bodies. The left-hand column tells us that an absolutely light body (fire) would naturally rise rectilinearly upward toward the lunar sphere, whereas the right-hand column informs us that an absolutely heavy body would fall naturally downward in a straight line toward the earth's center. Although Aristotle knew that earth was denser than air and water, he would have denied that density explained the fall of a stone through air or water. A stone falls only because it is absolutely heavy. Fire does not rise to its natural place near the surface of the lunar sphere because it is less dense than earth, water, or air, but rather because it is absolutely light. Indeed, fire does not even possess weight in its own natural place, so that if the air below were removed fire would not fall or move downward. With hindsight, we can now see that Aristotle's introduction of absolute heaviness and lightness was hardly conducive to the advance of physics, though Aristotle himself viewed it as a significant improvement over Plato and the atomists, who had attributed weight to all things, and for whom weight was a relative concept. Of the two possibilities before him, Aristotle chose the option that would prove historically least helpful. He did so, however, because he made his system heavily dependent on a variety of absolute contraries, choosing to avoid the relativistic comparisons of Plato and the atomists.

To provide a causal explanation for natural motion (and, as we shall see, for violent, or unnatural, motion as well), Aristotle invoked the general principle that every effect has a cause and assumes that every animate and inanimate thing capable of motion is moved by something else that is itself in motion or at rest.[5] (Or, to use the succinct medieval version of this principle: "everything that is moved is moved by another.") The mover and the thing moved were always assumed to be distinct entities. Although it might appear that natural motions would not require causal explanations because they are "natural," Aristotle assigned a particular agent (called the *generans*, or generator, in the Middle Ages) as the primary cause of unobstructed natural motion. The causative agent, or generator, was the thing that had originally produced the body actually in motion. For example, a fire produces another fire (as when a log is set ablaze) and confers on the new fire all the properties that belong to fire, one of which is the spontaneous ability to rise naturally when unimpeded. Similarly, whatever natural agent produces a stone confers upon it all of its essential properties, including the natural tendency to fall to earth when removed from its natural place.

Although he identified the *generans*, or the generator of a thing, as a kind of remote motive cause in natural motion, Aristotle interpreted the fall of a body as if its weight were the immediate cause of its natural downward motion; and he treated the rise of a body as if its lightness were the immediate cause of its natural upward motion. All other things being equal, Aristotle concluded that velocity is directly proportional to the weight of the body in natural motion and inversely proportional to the resistance it meets, which is measured by the density of the medium through which it moves, and that the time of its motion is directly proportional to the resistance, or density, of the medium and inversely proportional to its weight. For example, the speed of a body could be doubled either by doubling its weight (but holding the medium constant) or halving the density of the medium (and holding the weight of the body constant). Similarly, the time of motion could be doubled either by doubling the density of the medium (but keeping the weight constant) or by halving the weight of the body (and holding the density of the medium constant). Despite his recognition that unimpeded heavy bodies accelerated as they approached their natural places, Aristotle discussed natural motions as if their speeds were uniform.

Violent, or unnatural, motion. Motions that are violent, or unnatural, occur when bodies are pushed out of, or away from, their natural places. Thus a stone that is thrown rectilinearly upward into the air, or is hurled with a horizontal trajectory, is in violent motion; the motion of a fire that is somehow forced downward out of its natural place toward the earth is unnatural, or violent. Similarly, the motion of air when it is forced out of its natural place down toward the earth or upward toward the natural place of fire is characterized as a violent motion. Aristotle formulated specific rules in which he described the consequences that would follow from the application of a motive force to a resisting object. Although the rules are couched in terms of force, resisting body, distance traversed, and time, rather than directly in terms of velocity, the latter permits a more convenient summary. The velocity of a body in violent motion is inversely proportional to its own resistive power, which is left undefined, and directly proportional to the motive power, or applied force. In symbols, $V \propto F/R$, where V is velocity, F is motive force, and R is the total resistance offered to the applied force, a quantity that, presumably, includes the resisting object or body plus the resistance of the external medium in which the motion occurs. To double a velocity, V, the resistance R could be halved and F held constant; or, F doubled and R held constant. To halve V, F could be halved and R held constant; or R doubled and F held constant.

Violent motion required a radically different causal explanation than did natural motion. The initial mover, or causal agent, was readily identifiable because it had to be in direct physical contact with the body it moved. Someone throwing a stone upward or pushing a wagon along a road is the mover, or motive power, in those violent motions. But the source of power that enabled a body to continue its motion after losing contact with its initial mover was far from obvious. How, for example, did a stone continue its motion after losing contact with the hand of a child that threw it? Aristotle argued that the external medium – air in the example of a stone – was the source of continuous movement. He believed that the original mover not only puts the stone in motion but also activates the air simultaneously. Apparently, the first portion or unit of activated air pushes the stone and simultaneously activates the adjacent, or second, unit of air which moves the stone a bit further. The second unit, in turn, simultaneously activates the next, or third, unit of air, and so on. As the process continues, the motive power of the successive units of air gradually diminishes until a unit of air is reached that is only capable of activating the very next unit of air, but is unable to communicate to it the power to move the body further. At that point, the stone begins to fall with its natural downward motion. By this mechanism, Aristotle employed the medium as both motive power and resistance. Not only did he believe that the medium as motive force had to be in constant physical contact with the body it moved, but he was equally convinced that the same medium had to function as a brake on the motion of that same body in order to prevent the impossible: the occurrence of an infinite speed, or an instantaneous motion. Aristotle took it as obvious that resistance to motion increased as the density of the medium increased, and decreased as the medium was rarefied. Because an indefinite rarefaction of the medium would result in a proportionate and indefinite increase in speed, Aristotle concluded that if a medium vanished entirely, leaving a vacuum, motion would be instantaneous (or beyond any ratio, as he put it).

The absurdity of an infinite speed was only one of a number of arguments that prompted Aristotle to reject the existence of a vacuum. The fundamental principles that he believed operative in the world would be useless in void spaces. Motion would be impossible for a number of reasons. The homogeneous nature of an extended void space meant that every part must be identical to every other part. Because differentiable natural places could not exist in a homogeneous space, bodies would have no good reason for moving in one direction rather than another. Natural motions would be impossible, as would violent motions, because the external medium Aristotle deemed essential for violent motion would be absent. If the void were infinite, and motion could somehow occur, that motion either would be unending – for what would stop a body in motion in a void that lacked other bodies and natural places to bring it to rest – or, in the absence of external resistances, it would be instantaneous. Among Aristotle's remaining arguments against the void, one is noteworthy. Bodies of different weights would necessarily fall in a void with equal velocities, which Aristotle regarded as an absurdity, because they ought to fall with speeds that are directly proportional to their respective weights. But the latter relationship could only occur in a plenum, where a heavier body cleaves through the material medium more easily than does a less heavy body. In the absence of a medium, Aristotle saw no plausible reason why one body should move with a greater speed than another. He therefore concluded that the world was necessarily a plenum, filled everywhere with matter.

THE CELESTIAL REGION: INCORRUPTIBLE AND CHANGELESS

The part of the world that Aristotle envisioned beyond the convex surface of the sphere of fire was radically different from the terrestrial part just described. Aristotle regarded the celestial region as so incomparably superior to the terrestrial that he assigned to it properties that emphasized these profound differences. If incessant change was basic to the terrestrial region, then lack of change had to characterize the celestial region. This conviction was reinforced for Aristotle by his belief that human records revealed no changes in the heavens. Because the four elements of the sublunar region were involved in ceaseless change, they were obviously unsuitable for the changeless heavens. In his *On the Heavens* (bk. 1, chs. 2 and 3), Aristotle contrasted the natural rectilinear motion of the four sublunar elements (earth, water, air, and fire) with the observed regular, and seemingly natural, circular motion of the planets and fixed stars in the celestial region. The contrast between the straight line and the circle, the former finite and incomplete, the latter closed and complete in itself, convinced Aristotle, if he needed convincing, that the circular figure was necessarily and naturally prior to the rectilinear figure. Because the four simple elemental bodies moved with natural rectilinear (upward and downward) motion, Aristotle concluded that the observed circular motion of the celestial bodies must necessarily be associated with a different kind of simple, elemental body: a fifth element, or ether.

As if to emphasize the special importance of the ether, Aristotle often called it the "first body." Its primary properties were almost the opposite of those of the terrestrial elements. Where terrestrial elements moved naturally with rectilinear motions, the ether moved naturally with circular motion, which was superior because the circle was complete in itself, whereas the straight line was not. Where the four elements and the bodies compounded of them were in a continual state of flux, the celestial ether suffered no substantial, qualitative, or quantitative changes. Substantial change was impossible because Aristotle assumed that the pairs of opposite, or contrary, qualities, such as hotness and coldness, wetness and dryness, rare and dense, which were basic forces for change in the terrestrial region, were absent from the heavens and therefore played no role there. Aristotle's rejection of contrary qualities in the heavens led him to deny the existence there of the contrary qualities lightness and heaviness, from which he concluded that the celestial ether could be neither light nor heavy. Lightness and heaviness in the terrestrial region were associated with upward and downward rectilinear motions: heavy bodies approached the earth when they moved naturally downward, and light bodies receded from the earth when they moved naturally upward. In the absence of heaviness and lightness in the heavenly region, Aristotle inferred that rectilinear motions could not occur there. Thus not only was it observationally evident that the celestial motions were circular, but, from the very properties of the ether itself, it was apparent to Aristotle that rectilinear motions were impossible in the celestial region.

Because planets and stars are observed to move around the sky, Aristotle inferred that change of position was the only kind of change possible in the heavens. Celestial bodies continually change their positions by moving around the sky with effortless, uniform, circular motion. This uniform, circular motion is a natural motion, just as rectilinear up-and-down motions are natural. But where up and down were contrary terrestrial motions, circular motion had no contrary. Aristotle concluded that circular motion, which lacked a contrary motion, was natural to bodies composed of celestial ether, which lacked contrary qualities. In the absence of all contraries, change as it was observed in the terrestrial

region could not occur in the ethereal heavens. Celestial bodies had to move eternally around the heavens with natural, uniform, circular motion. Although they changed positions, the absence of contraries prevented variations in their distances. Aristotle thus assumed that celestial bodies neither approached the earth, nor receded from it.

Aristotle associated change with matter, but he denied change in the heavens. Did it follow then that the heavens lacked matter and that the celestial ether, whatever else it might be, was not to be thought of as matter? On this important issue, Aristotle's remarks are inconclusive, and medieval natural philosophers were left to ponder his meaning. Both interpretations – that matter exists and does not exist in the heavens – received support.

Whether or not it was to be construed as matter, the celestial ether posed other problems. Because it was a perfect substance extending from the moon to the fixed stars, Aristotle seems to have thought of the ether as homogeneous, with all its parts identical. A glance at the heavens should have dispelled such a notion. At the very least, the celestial region consisted of visible bodies surrounded by empty portions of sky, a configuration that hardly suggests homogeneity. If celestial bodies and empty sky were both composed of the same ether, why did they differ? Why were planets and stars visible, and the rest of the sky effectively invisible? If the planets were made of the same ether, why did they seem to differ from one another? Why did their properties vary? To these questions, Aristotle supplied no answers, perhaps because the questions never occurred to him. When such questions occurred to his Greek, Arabic, and Latin commentators, they had to devise their own responses, a common fate for those who spent much of their lives seeking the meanings of Aristotle's texts.

On the nature of the empty celestial spaces, however, Aristotle was quite clear: they were filled with invisible, transparent, ethereal spheres that were nested one with another and each of which turned with regular, uniform, motion. Celestial bodies – planets and fixed stars – were somehow embedded in these spheres and carried around by them. Aristotle based his system upon the earlier mathematical systems of concentric spheres devised by Eudoxus of Cnidus and Callippus of Cyzicus in the fourth century B.C. In the latter's scheme, on which Aristotle directly founded his cosmology of concentric spheres, the planet Saturn, for example, was assigned a total of four spheres that were supposed to account for its celestial position. Of these, one was for Saturn's daily motion; one was for its proper motion along the zodiac, or ecliptic; and two represented its observed retrograde motions along the zodiac. Aristotle transformed Callippus's mathematical spheres into a system of real, earth-centered, physical celestial orbs that were collectively coterminous with the celestial region. To prevent the transmission of Saturn's zodiacal and retrograde motions to Jupiter, the planet immediately beneath Saturn, Aristotle added three "unrolling," or counteracting, spheres for Saturn. The purpose of the three unrolling spheres was to counteract the motions of three of Saturn's four spheres, with the exception of the sphere representing the daily motion (because the daily motion was common to all planets, each was assigned a special sphere for that purpose, thus acknowledging that the daily motion was transmissible through each set of planetary spheres). As D. R. Dicks explains it:

> Thus for the four spheres of Saturn, A, B, C, D, a counteracting sphere D' is postulated, placed inside D (the sphere nearest the earth and carrying the planet on its equator) and rotating round the same poles and with the same speed as D but in the opposite direction; so that the motions of D and D' effectually cancel each other out, and any point on D will appear to move only according to the motion of C. Inside D' a second counteracting sphere C' is placed, which performs the same function for C as D' does for D; and inside C' is a third counteracting sphere B' which similarly cancels out the motion of B. The net result is that the only motion left is that of the outermost sphere of the set, representing the diurnal rotation, so that the spheres of Jupiter (the next planet down) can now carry out their own revolutions as if those of Saturn did not exist. In the same manner, Jupiter's counteracting spheres clear the way for those of Mars, and so on (the number of counteracting spheres in each case being one less than the original number of spheres in each set) down to the moon which, being the last of the planetary bodies (i.e. nearest the earth), needs, according to Aristotle, no counteracting spheres.[6]

Instead of the four spheres that Callippus required for Saturn, we see that Aristotle assigned seven. Similarly, he thought it necessary to add counteracting, or unrolling, spheres for all the planets, except the Moon, located directly above the sublunar region. Thus did Aristotle move from Callippus's system of thirty-three mathematical, or hypothetical, spheres to fifty-five physical orbs.

A momentous question was immediately posed: what caused the orbs to move around with uniform, circular motion as they carried the planets and stars? Aristotle transmitted a dual, and conflicting, legacy. In his cosmological treatise, *On the Heavens*, he appealed to an internal principle of movement when he described the celestial ether as a "simple body naturally so constituted as to move in a circle in virtue of its own nature" (2.1.284a.14–15). But in his *Physics* and *Metaphysics*, Aristotle assumed that external spiritual movers, or intelligences, were the causative agents of the rotary motions of celestial orbs. In this scheme, Aristotle assumed that each physical orb had its own immaterial mover, which, although completely immobile, was eternally able to cause its assigned orb to move effortlessly around the earth with uniform, circular motion. These "immovable," or "unmoved," movers were unique in the world because they were capable of causing motion without themselves being in motion. The potentially infinite regress of causes and effects for all motions came to a halt with the unmoved movers, which were thus the ultimate immobile sources of all motions. Although Aristotle spoke of fifty-five unmoved movers, his concept of God focused on the unmoved mover associated with the sphere of the fixed stars, the outermost circumference of the world. For Aristotle, this most remote of unmoved movers was the "prime mover," which enjoyed a special status as first among equals. Nevertheless, its role as a celestial mover differed in no way from that of all other unmoved movers, or intelligences, as they were usually called.

How did an immaterial unmoved mover cause a physical orb to move? "It produces motion by being loved" was Aristotle's response (*Metaphysics* 12.7.1072b.3–4). Precisely what he meant by this, Aristotle left unexplained. How were the motive cause and the thing moved related? Not only did his cryptic phrase tax the ingenuity of many subsequent commentators, but the intriguing thought of love as a cosmic motive force also seems to have captured the fancy of poets and jongleurs. In the last line of the *Divine Comedy*, Dante speaks of "The love that moves the sun and the other stars" (*l'amor che move il sole e l'altre stelle*),[7] and an anonymous French song proclaims "Love, love makes the world go round" (*L'amour, l'amour fait tourner le monde*).[8] If an English-language counterpart failed to appear in the Middle Ages or the Renaissance, it finally emerged in the Gilbert and Sullivan operetta *Iolanthe*, where we learn that "It's love that makes the world go round."[9] Although it is by no means certain that Aristotle is the ultimate source of these poetic sentiments, he is surely a – if not *the* – leading candidate.

Because he characterized the celestial ether as a divine and incorruptible substance and viewed terrestrial matter as the source of incessant change by means of generation and corruption, Aristotle was convinced that the unchanging celestial region exercised a dominant influence on the always changing terrestrial region. It was fitting that a nobler and more perfect thing should influence a less noble and less perfect thing. Here also was a powerful reinforcement for traditional astrological belief. The various ways in which celestial dominance was effected exercised the minds of natural philosophers until the end of the seventeenth century when the conception of the cosmos was radically altered. But as with the cause of celestial motion, Aristotle left an ambiguous legacy. Although Aristotle believed that terrestrial bodies were subject to celestial domination, he also believed that they were capable of causing effects by themselves, and were not merely passive entities dependent on celestial causes. As entities composed of matter and form, terrestrial bodies possessed natures of their own that were capable of producing effects. A heavy body fell toward the center of the earth not by virtue of any celestial power but because it possessed a nature that enabled it to do so when otherwise unimpeded. Each species of animate and inanimate being had characteristic features and properties that enabled its individual members to act in accordance with those properties.

The model for celestial activity and influence on terrestrial affairs was undoubtedly the Sun, whose influences were manifest and palpable. Its annual march around the ecliptic produced the seasons, which in turn produced various generations and corruptions. Human generation was also dependent on the Sun, as evidenced by Aristotle's widely quoted assertion that "man is begotten by man and by the sun as well."[10] With the exception of the Moon, evidence for celestial activity by the other planets was virtually nonexistent. Nevertheless, Aristotle assumed that they were also actively involved in terrestrial change. But he failed to explain how the activities of celestial bodies other than the Sun were related to the independent natures of terrestrial bodies. Once again, subsequent commentators were left to their own devices.

Many of Aristotle's major ideas and concepts about the physical world have now been described. Not only were they instrumental in shaping medieval views about the ways in which changes occurred in the terrestrial region but they also explained why these same changes were assumed not to occur in the celestial region. The ideas described here formed the core of medieval natural philosophy, and some, if not many, of those ideas would serve as springboards into new areas of thought. Aristotle's ideas provided not only a skeletal frame for medieval natural philosophy but also much of the muscle and tissue. And yet there are themes about which Aristotle provided little guidance, because either the topic was unknown to him or he had little to say about it. On other occasions, he was vague, unclear, or ambiguous, and his commentators had to work things out for themselves. At other times, his explanations were seen to be inadequate and cried out for replacement. Occasionally, his interpretations were drastically modified on the basis of experience, as with his system of concentric orbs, or on the basis of Christian theology, as with the eternity of the world. In much, if not most, of what he said, however, Aristotle's ideas were utilized as the best and most reliable guides to the comprehension of nature and its works. To medieval scholars, he was truly the Philosopher. In his commentary on Aristotle's *On the Heavens* (*De caelo*), Averroes paid Aristotle the highest possible tribute, declaring that Aristotle was

> a rule and exemplar which nature devised to show the final perfection of man . . . the teaching of Aristotle is the supreme truth, because his mind was the final expression of the human mind. Wherefore it has been well said that he was created and given to us by divine providence that we might know all that is to be known. Let us praise God, who set this man apart from all others in perfection, and made him approach very near to the highest dignity humanity can attain.[11]

David Knowles, a historian of medieval philosophy, was not exaggerating when he called this "the most impressive eulogium ever given by one great philosopher to another."[12] Indeed, Averroes considered Aristotle to be virtually infallible because in over one thousand years no error had been detected in his writings.[13]

Aristotle was also greatly admired in the Latin West. Dante spoke for many when he described Aristotle as "the Master of them that know."[14] Thomas Aquinas regarded Aristotle as someone who had attained the highest possible level of human thought without benefit of the Christian faith. We might suppose that with such reverential attitudes medieval scholars would have sought to stay as close as possible to the great master. But for reasons already given, they often moved away. In chapter 6, I describe the manner in which Aristotle's medieval disciples and admirers altered and expanded his natural philosophy, even as they upheld its basic principles and remained faithful to its overall spirit. Before that, however, I shall describe the turbulent introduction of Aristotelian natural philosophy into Europe during the thirteenth century.