FIVE

Science in the Renaissance

To appreciate Leonardo's science, it is important to understand the cultural and intellectual context in which he created it. Scientific ideas do not occur in a vacuum. They are always shaped by cultural perceptions and values, and by the technologies available at the time. The entire constellation of concepts, values, perceptions, and practices—the "scientific paradigm" in the terminology of science historian Thomas Kuhn—provides the context that is necessary for scientists to pose the great questions, organize their subjects, and define legitimate problems and solutions.[1] All science is built upon such an intellectual and cultural foundation.

Hence, when we recognize ancient or medieval ideas reflected in Leonardo's scientific writings, this does not mean that he was less of a scientist, as has sometimes been asserted. On the contrary: Like every good scientist, Leonardo consulted the traditional texts and used their conceptual framework as his starting point. He then tested the traditional ideas against his own scientific observations. And, in accordance with scientific method, he did not hesitate to modify the old theories when his experiments contradicted them.

THE REDISCOVERY OF THE CLASSICS

Before we examine how Leonardo developed his scientific method, we need to understand the principal ideas of ancient and medieval natural philosophy, which formed the intellectual context within which he operated.[2] Only then will we be able to truly appreciate the transformative nature of his accomplishments.

The ideas of Greek philosophy and science, on which the Renaissance worldview was based, were ancient knowledge. Yet for Leonardo and his contemporaries, they were fresh and inspiring, because most of them had been lost for centuries. They had been rediscovered only recently in the original Greek texts and in Arabic translations. As the Italian humanists studied a wide variety of classical texts and their Arabic elaborations and critiques, the Renaissance rediscovered the classics, as well as the concept of critical thinking.

During the Early Middle Ages (sixth through tenth centuries A.D.), also known as the Dark Ages, Greek and Roman literature, philosophy, and science were largely forgotten in Western Europe. But the ancient texts had been preserved in the Byzantine Empire, along with the knowledge of classical Greek.[3] And so the Italian humanists repeatedly journeyed to the East, where they acquired hundreds of classical manuscripts and brought them to Florence. They also established a chair of Greek at the Studium Generale, as the University of Florence was called, and attracted eminent Greek scholars to help them read and interpret the ancient texts.

In antiquity, the Romans were in awe of Greek art, philosophy, and science, and their noble families often employed Greek intellectuals as tutors for their children. But the Romans themselves hardly produced any original science. However, Roman architects and engineers wrote many important treatises, and Roman scholars condensed the scientific legacy of Greece into large encyclopedias that were popular during the Middle Ages and the Renaissance. These Latin texts were eagerly consulted by the humanist artists and intellectuals, and some were translated into the Italian vernacular.

In the seventh century, powerful Muslim armies, inspired by the new religion of Islam, burst forth from the Arabian peninsula and in successive invasions conquered peoples in the Middle East, across North Africa, and in southern Europe. As they built their vast empire, they not only spread Islam and the Arabic language, but also came in contact with the ancient texts of Greek philosophy and science in the Byzantine libraries. The Arabs deeply appreciated Greek learning, translated all the important philosophical and scientific works into Arabic, and assimilated much of the science of antiquity into their culture.

In contrast to the Romans, the Arab scholars not only assimilated Greek knowledge but examined it critically and added their own commentaries and innovations. Numerous editions of these texts were housed in huge libraries throughout the Islamic empire. In Moorish Spain, the great library of Córdoba alone contained some six hundred thousand manuscripts.

When the Christian armies confronted Islam in their military crusades, their spoils often included the works of Arab scholars. Among the treasures left behind by the Moors in Toledo when they retreated was one of the finest Islamic libraries, filled with precious Arabic translations of Greek scientific and philosophical texts. The occupying forces included Christian monks, who quickly began to translate the ancient works into Latin. A hundred years later, by the end of the twelfth century, much of the Greek and Arabic philosophical and scientific heritage was available to the Latin West.

Islamic religious leaders emphasized compassion, social justice, and a fair distribution of wealth. Theological speculations were seen as being far less important and therefore discouraged.[4] As a result, Arab scholars were free to develop philosophical and scientific theories without fear of being censored by their religious authorities.

Christian medieval philosophers did not enjoy such freedom.

Unlike their Arab counterparts, they did not use the ancient texts as the basis for their own independent research, but instead evaluated them from the perspective of Christian theology. Indeed, most of them were theologians, and their practice of combining philosophy—including natural philosophy, or science—with theology became known as Scholasticism. While early Scholastics, led by Saint Augustine, attempted to integrate the philosophy of Plato into Christian teachings, the height of the Scholastic tradition was reached in the twelfth century, when the complete writings of Aristotle became available in Latin, usually translated from Arabic texts. In addition, the commentaries on Aristotle by the great Arab scholars Avicenna (Ibn Sina) and Averroës (Ibn Rushd) were translated into Latin.

The leading figure in the movement to weave the philosophy of Aristotle into Christian teachings was Saint Thomas Aquinas, one of the towering intellects of the Middle Ages. Aquinas taught that there could be no conflict between faith and reason, because the two books on which they were based—the Bible and the "book of nature"—were both authored by God. Aquinas produced a vast body of precise, detailed, and systematic philosophical writings in which he integrated Aristotle's encyclopedic works and medieval Christian theology into a magnificent whole.

The dark side of this seamless fusion of science and theology was that any contradiction by future scientists would necessarily have to be seen as heresy. In this way, Thomas Aquinas enshrined in his writings the potential for conflicts between science and religion—which indeed arose three centuries later in Leonardo's anatomical research,[5] reached a dramatic climax with the trial of Galileo, and have continued to the present day.

THE INVENTION OF PRINTING

The sweeping intellectual changes that took place in the Renaissance and prepared the way for the Scientific Revolution could not have happened without a technological breakthrough that changed the face of the world—the invention of printing. This momentous advance, which took place around the time of Leonardo's birth, actually involved a double invention, that of typography (the art of printing from movable type) and that of engraving (of printable pictures). Together, these inventions marked the decisive threshold between the Middle Ages and the Renaissance.

Printing introduced two fundamental changes to the distribution of texts: rapid diffusion and standardization. Both were of tremendous importance for the spread of scientific and technological ideas. Once a page had been composed by the typesetters, it was easy to produce and distribute hundreds or thousands of copies. Indeed, after Johannes Gutenberg printed his famous forty-two-line Bible in Mainz around 1450, the art of printing spread across Europe like wildfire. By 1480 there were over a dozen printers in Rome, and by the end of the century Venice boasted around one hundred printers, who turned this city of great wealth into the foremost printing center of Europe. It has been estimated that the Venetian printers alone produced about 2 million volumes during the fifteenth century.[6]

For the rise of science, the production of standard texts was as important as their wide dissemination. With the use of the printing press, texts could not only be copied exactly, but were also laid out identically in each copy, so that scholars in different geographical locations could refer to a particular passage on a specific page without ambiguity. This had never been easy, nor dependable, in hand-copied medieval manuscripts.

The production of standard copies of images that served as illustrations of texts was perhaps even more important, and this is where the invention of engraving became an indispensable complement to typography. Whereas the pictures in ancient manuscripts often lost detail with each new manual copy, the use of woodcuts and copper plates now made it possible to reproduce illustrations of plants, anatomical details, mechanical devices, scientific apparatus, and mathematical diagrams with complete accuracy. Those images were valuable standards to which scholars could easily refer.

Leonardo was well aware of these tremendous advantages of printing and keenly interested in the technical details of the printing process throughout his life.[7] Among his earliest drawings of mechanical devices in the Codex Atlanticus, from the years 1480–82, is one of a typographic press with an automatic page feeder, an innovation that

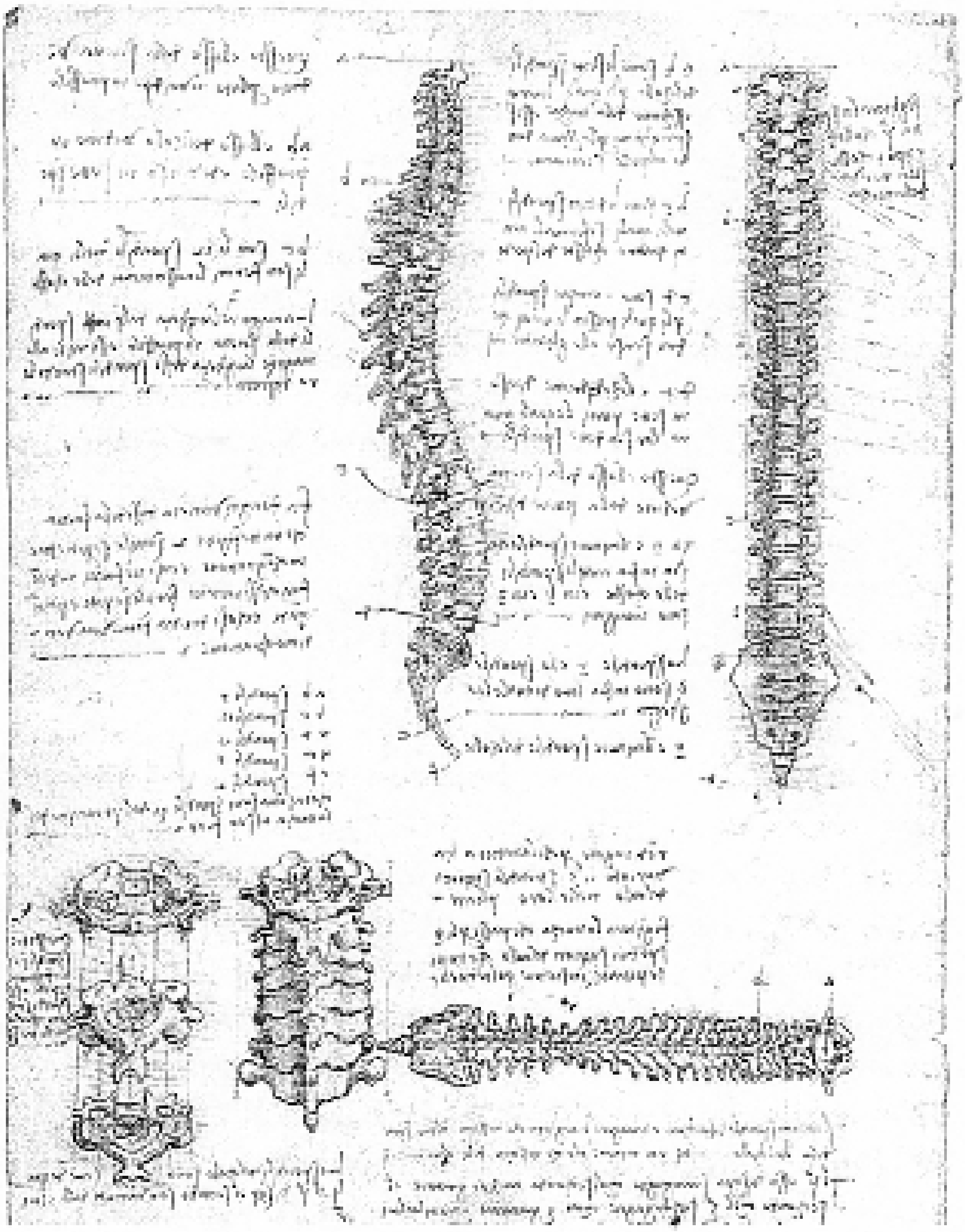

Figure 5-1: The vertebral column, c. 1510, Anatomical Studies, folio 139v

was to reappear a couple of decades later. As he expanded his scientific research, Leonardo became increasingly aware of the need to disseminate printed versions of his treatises. Around 1505, while he painted *The Battle of Anghiari* in Florence and wrote his Codex on the Flight of Birds, he even invented a novel printing method for the simultaneous reproduction of texts and drawings. This was an extraordinary forerunner of the method introduced in the late eighteenth century by the

Romantic poet and artist William Blake, who was also a professional engraver.[8]

A few years later, at the height of his anatomical work in Milan, Leonardo added a technical note about the reproduction of his drawings to his famous assertion of the superiority of drawing over writing.[9] He insisted that his anatomical drawings should be printed from copper plates, which would be more expensive than woodcuts but much more effective in rendering the fine details of his work. "I beg you who come after me," he wrote on the sheet that contains his magnificent drawings of the vertebral column (Fig. 5-1), "not to let avarice constrain you to make the prints in [wood]."[10]

THE WORLD OF EXPLORATION

While explorations of the rediscovered classical texts greatly extended the intellectual frontiers of the Italian humanists, their physical frontiers were also being extended by the geographical discoveries of the famous Portuguese explorers and those who followed them. The Renaissance was the golden age of geographical exploration. By 1600 the surface of the known world had doubled since medieval times. Entirely new regions, new climates, and new aspects of nature were being discovered. These explorations generated a strong interest in biology, or "natural history" as it was called at the time, and the great ocean voyages led to numerous improvements in shipbuilding, cartography, astronomy, and other sciences and technologies associated with navigation.

In addition to the explorers' seafaring voyages, new regions of the Earth were being discovered, even in the very heart of Europe when the first mountaineers ventured into the higher altitudes of the Alps. During the Middle Ages it had been commonly believed that the high mountains were dangerous, not only because of the severity of their climates but also because they were the abodes of gnomes and devils. Now, with the new humanist curiosity and confidence in human capabilities, the first Alpine expeditions were being undertaken, and by the end of the sixteenth century, close to fifty summits had been reached.[11]

Leonardo fully embraced the humanist passion for exploration, in both the physical and mental realms. He was one of the first European mountaineers[12] and traveled frequently within Italy, exploring the vegetation, waterways, and geological formations of the regions he visited. In addition, he delighted in composing fictitious tales of journeys to mountains and deserts in faraway countries.[13]

These few examples from Leonardo's many interests and activities show us that he was well aware of the intellectual, technological, and cultural achievements of his time. From his early days as an apprentice in Verrocchio's workshop through the years he spent at various European courts, he was in regular contact with leading artists, engineers, philosophers, historians, and explorers, and thus thoroughly familiar with the wide range of ideas and practices that we now associate with the Renaissance.

THE ANCIENT VIEW OF THE UNIVERSE

The foundation of the Renaissance worldview was the conception of the universe that had been developed in classical Greek science: that the world was a *kosmos*, an ordered and harmonious structure. From its beginnings in the sixth century B.C., Greek philosophy and science understood the order of the cosmos to be that of a living organism rather than a mechanical system. This meant that all its parts had an innate purpose to contribute to the harmonious functioning of the whole, and that objects moved naturally toward their proper places in the universe. Such an explanation of natural phenomena in terms of their goals, or purposes, is known as teleology, from the Greek *telos* (purpose). It permeated virtually all of Greek philosophy and science.

The view of the cosmos as an organism also implied for the Greeks that its general properties are reflected in each of its parts. This analogy between macrocosm and microcosm, and in particular between the Earth and the human body, was articulated most eloquently by Plato in his *Timaeus* in the fourth century B.C., but it can also be found in the teachings of the Pythagoreans and other earlier schools. Over time, this idea acquired the authority of common knowledge, which continued throughout the Middle Ages and into the Renaissance.

In early Greek philosophy, the ultimate moving force and source of all life was identified with the soul, and its principal metaphor was that of the breath of life. Indeed, the root meaning of both the Greek *psyche* and the Latin *anima* is "breath." Closely associated with that moving force—the breath of life that leaves the body at death—was the idea of knowing. For the early Greek philosophers, the soul was both the source of movement and life, and that which perceives and knows. Because of the fundamental analogy between micro- and macrocosm, the individual soul was thought to be part of the force that moves the entire universe, and accordingly the knowing of an individual was seen as part of a universal process of knowing. Plato called it the *anima mundi*, the "world soul."

As far as the composition of matter was concerned, Empedocles in the fifth century B.C. claimed that the material world was composed of varying combinations of four elements—earth, water, air, and fire. When left to themselves, the elements would settle into concentric spheres with the earth at the center, surrounded successively by the spheres of water, air, and fire. Farther outside were the spheres of the planets and beyond them was the sphere of the stars.

According to the four-element theory, the great variety of qualities we observe in material objects is the result of combinations of four pairs of qualities associated with the elements: cold and dry (earth), hot and dry (fire), cold and wet (water), and hot and wet (air). Half a century after Empedocles, an alternative theory of matter was proposed by Democritus, who taught that all material objects are composed of atoms of numerous shapes and sizes, and that all observable qualities are derived from the particular combinations of atoms inside the objects. His theory was so antithetical to the traditional teleological views of matter that it was pushed into the background, where it remained throughout the Middle Ages and the Renaissance. It would surface again only in the seventeenth century, with the rise of Newtonian physics.[14]

Even if the properties of material objects could be seen as arising from various combinations of the basic qualities inherent in the four elements, the Greek philosophers still faced the problem of how these combinations of elements acquired the specific forms we see in nature. The first philosopher to address the problem of form was Pythagoras in the sixth century B.C., who founded a cultlike school of mathematics, known as Pythagoreans. He and his disciples believed that numerical patterns and ratios were at the origin of all forms. With this association between the concrete world of natural forms and the abstract realm of numerical relationships began the link between science and mathematics that would become the foundation of classical physics in the seventeenth century.

The Pythagoreans divided the universe into two realms: the heavens, in which the stars revolve in celestial spheres according to perfect, unchanging mathematical laws; and the Earth, in which phenomena are complex, ever changing, and imperfect. Plato added his own refinement to this picture. Since the circle is the most perfect geometrical figure, he argued, the planets, like the stars, must move in circles.

ARISTOTLE'S SYNTHESIS OF SCIENCE

For science at the time of the Renaissance, the most important Greek philosopher was Aristotle. A student of Plato, Aristotle was by far the most brilliant in Plato's Academy. But he was quite different not only from his teacher, but also from all his predecessors. Aristotle was the first philosopher to write systematic, professorial treatises about the main branches of learning of his time. He synthesized and organized the entire scientific knowledge of antiquity in a scheme that would remain the foundation of Western science for two thousand years. And when this body of knowledge was fused with Christian theology in the Middle Ages, it acquired the status of religious dogma.

To integrate the main disciplines of his time—biology, physics, metaphysics, ethics, and politics—into a coherent theoretical framework, Aristotle created a formal system of logic and a set of unifying principles. He stated explicitly that the goal of his logic was to learn the art of scientific investigation and reasoning. It was to serve as the rational instrument for all scientific work.

As a scientist, Aristotle was first and foremost a biologist, whose observations of marine life were unsurpassed until the nineteenth century. Like Pythagoras, he distinguished between matter and form, but as a biologist he knew that living form is more than shape, more than a static configuration of component parts.[15] His highly original approach to the problem of form was to posit that matter and form are linked through a process of development. In contrast with Plato, who believed in an independent realm of ideal forms, Aristotle held that form has no separate existence but is immanent in matter. Nor can matter exist separately from form. By means of form, the essence of matter becomes real, or actual. Aristotle called this process of the self-realization of matter *entelechy* (self-completion). Matter and form, in his view, are the two sides of this process of development, separable only through abstraction.

Aristotle associated his *entelechy* with the traditional Greek concept of the soul as the source of life.[16] The soul, for him, is the source not only of bodily motion but also of the body's formation: It is the form that realizes itself in the changes and movements of the organic body. Leonardo, as I shall show, adopted the Aristotelian concept of the soul, expanded it, and transformed it into a scientific theory based on empirical evidence.[17]

Aristotle conceived of the soul as being built up in successive levels, corresponding to levels of organic life. The first level is the "vegetative soul," which controls, as we would say today, the mechanical and chemical changes of the body's metabolism. The soul of plants is restricted to this metabolic level of a vital force. The next higher form is the "animal soul," characterized by autonomous motion in space and by sensation, that is, feelings of pleasure and pain. The "human soul," finally, includes the vegetable and animal souls, but its main characteristic is reason.

In terms of physics and astronomy, Aristotle adopted the Pythagorean antithesis between the terrestrial and the heavenly worlds. From the Earth to the sphere of the Moon, he taught, all things constantly change, generating new forms and then decaying again; above the Moon, the crystalline spheres of the planets and stars revolve in eternal, unchanging motions. He subscribed to the Platonic idea that the perfection of the celestial realm implies that the planets and stars move in perfect circles. Aristotle also accepted Plato's view that divine souls reside in the heavenly bodies, and that they influence life on Earth. This idea lies at the root of medieval astrology, which was still very popular during the Renaissance. Leonardo, however, emphatically rejected it.[18]

Following Empedocles, Aristotle maintained that all forms in the world arise from various combinations of the four elements—earth, water, air, and fire—and he saw the ever-changing mixtures of elements as the source of the imperfection and accidental nature of material forms. The four elements did not always remain in their assigned realms, he stated, but were constantly disturbed and being pushed into neighboring spheres, whereupon they would naturally try to return to their proper places. With this argument, Aristotle tried to explain why rain falls downward through the air, while air drifts upward in water, and the flames of fire rise up into the air. He strongly opposed the attempt by Democritus to reduce the qualities of matter to quantitative relations between atoms. It was because of Aristotle's great authority that the atomism of Democritus was eclipsed by teleological explanations of physical phenomena throughout antiquity and the Middle Ages.

For Aristotle, all activities that occurred spontaneously were natural, guided by the goals inherent in physical phenomena, and hence observation was the proper means of investigating them. Experiments that altered natural conditions in order to bring to light some hidden properties of matter were unnatural. As such, they could not be expected to reveal the essence of the phenomena. Experiments, Aristotle taught, were therefore not proper means of investigation, and indeed the experimental method was not essential to Greek science.

Aristotle's treatises were the foundation of philosophical and scientific thought in the Renaissance. But the humanist scholars also read Plato and various texts from the earlier traditions of Greek natural philosophy as well as the more recent treatises by Arab scientists. Thus, different schools of thought soon arose that followed one or another of the ancient philosophers. In particular, there was a lively debate between the Platonists, for whom only ideas were real and the world of the senses was illusory, and the Aristotelians, for whom the senses provided reality and ideas were mere abstractions.

Florence under the Medici was the center of Platonism. Milan, under the influence of the universities of Padua and Bologna, was predominantly Aristotelian. Leonardo, who spent many years in both cities, was well aware of the philosophical debates between the two schools. Indeed, the tension between the Platonic fascination with mathematical precision and the Aristotelian attention to qualitative forms and their transformations surfaces again and again in his writings.[19]

Renaissance science as a whole was characterized by a literary rather than an empirical approach. Instead of observing nature, the Italian humanists preferred to read the classical texts. In the words of historian of science George Sarton, "To study geometry was to study Euclid; a geographical atlas was an edition of Ptolemy; the physician did not study medicine, he studied Hippocrates and Galen."[20]

The classical treatises rediscovered in the Renaissance covered a wide range of subjects, from art and literature to philosophy, science, architecture, and engineering. As far as science, or "natural philosophy," was concerned, the Renaissance scholars studied Greek and Arabic texts within three broad areas: mathematics and astronomy, natural history, and medicine and anatomy.

MATHEMATICS AND ASTRONOMY AT THE TIME OF LEONARDO

Greek theoretical mathematics began during the lifetime of Plato, in the fifth and fourth centuries B.C. The Greeks tended to geometrize all mathematical problems and seek answers in terms of geometrical figures. For example, they represented quantities by lengths of lines and products of two quantities by the area of rectangles. These methods even enabled them to deal with irrational numbers,[21] representing the number $\sqrt{2}$, for example, by the diagonal of a square with sides of length 1.

Several centuries earlier the Babylonians had developed a different approach to solving mathematical problems, now known as algebra, which began with simple arithmetic operations and then evolved into more abstract formulations with numbers represented by letters. The Greeks learned these numerical and algebraic methods together with Babylonian astronomy, but they transformed them into their geometrical language and continued to see mathematical problems in terms of geometry. Plato's Academy, the principal Greek school of natural philosophy for nine centuries, is said to have had a sign above its entrance, "Let no one enter here who does not know geometry."

The culmination of the early phase of Greek mathematics was reached around 300 B.C. with Euclid, who presented all of the geometry and other mathematics known in his day in a systematic, orderly sequence in his celebrated *Elements*. The thirteen volumes of this classical textbook were not only widely read during the Renaissance, but remained the foundation for the teaching of geometry until the end of the nineteenth century. About one hundred years after Euclid, Greek mathematics reached its final climax with Archimedes, a brilliant mathematician who wrote many important treatises in what we would now call mathematical physics. But he was never as popular as Euclid. His mathematical work was so advanced that it was not understood until many centuries later, and his great fame as an inventor eclipsed his reputation as a mathematician.

With the rise of Islam during the seventh and subsequent centuries, the Arab world became the center of mathematical studies. Arab mathematicians translated and synthesized the Greek texts and also commented on important influences from Mesopotamia and India. Of particular importance was the work of Muhammad al-Khwarzimi in the ninth century, whose *Kitab al jabr* was the most influential work on algebra from this period. The Arabic *al jabr* (binding together) in its title is the root of our modern word "algebra."[22]

Two centuries later, Persia produced an outstanding algebraist in the poet Omar Khayyam, the world-renowned author of the *Rubaiyat*, who was famous in his time for classifying cubic equations and solving many of them. Another Islamic scholar of that period who was very influential in the Renaissance was the Arab mathematician Alhazen (Ibn al-Haitham), who wrote a brilliant treatise on the "science of perspective," which included detailed discussions of geometrical optics and of the geometrical principles of vision and the eye's anatomy.

In the Renaissance, thus, mathematicians had access to two different approaches for solving mathematical problems, geometry and algebra. However, until the seventeenth century, geometry was considered to be more fundamental. All algebraic reasoning was justified in terms of geometrical figures in the tradition of Greek mathematics. In the seventeenth century, this dependence of algebra on geometry was reversed by René Descartes, the founder of modern philosophy and a brilliant mathematician, who invented a method for associating algebraic equations with curves and surfaces.[23] This method, now known as analytic geometry, involves using Cartesian coordinates, the system invented by Descartes and named after him. Long before Descartes, however, the fields of geometry and algebra were related because both of them were necessary for the development of an accurate science of astronomy.

For astronomy was surely the principal physical science throughout antiquity. The Babylonians successfully applied their numerical methods to compile astronomical tables. The Greeks used their geometrical approach to construct elaborate cosmological models, involving the use of trigonometry—which the Greek astronomers had learned from Hindu mathematicians—to determine the distances between celestial bodies from their observed angular positions.

When the conquests of Alexander the Great made the observations and mathematical methods of the Babylonian astronomers available to the Greeks, they found it impossible to reconcile this improved data with their Platonic idea of circular planetary orbits. Several Greek astronomers therefore abandoned the Platonic-Aristotelian view and began to devise complex geocentric systems of cycles and epicycles to account for the movements of the sun, moon, and planets. The culmination of this development was reached in the second century A.D. with the Ptolemaic system, which predicted the motion of the planets with considerable accuracy.

Ptolemy's thirteen-volume treatise, *He mathematike syntaxis (The Mathematical Collection)* summarized much of this ancient astronomical knowledge. It remained the authoritative text on astronomy for fourteen centuries. (It is indicative of the prestige of Islamic science that the text was known throughout the Middle Ages and the Renaissance under its Arabic title, *Almagest*.) Ptolemy also published the *Geography*, which contained detailed discussions of cartographic techniques and an elaborate map of the known world. The book was printed in the fifteenth century under the title *Cosmography* and became the most popular geographical book printed from movable type during the Renaissance.

NATURAL HISTORY

Throughout antiquity and in the centuries that followed, the study of the living world was known as natural history, and those who pursued it were known as naturalists. This was often an amateur activity rather than a professional occupation. It was only in the nineteenth century that the term "biology" began to be widely used, and even then, biologists often continued to be called "naturalists."

In the fifteenth century, books about natural history still tended to display some fascination with the fabulous, often imaginary beasts that had populated medieval bestiaries. At the time of Leonardo, the rediscovery of classical natural history texts, together with the explorations of new floras and faunas in the Americas, began to stimulate more serious interest in the study of living things. The ideas of the ancient natural philosophers about plants and animals were represented in great detail in the encyclopedic works of Aristotle, Theophrastus, Pliny the Elder, and Dioscorides.[24]

Aristotle was the classical author most widely available to Renaissance scholars. His numerous works included several treatises on animals, including the *Historia animalium (History of Animals)* and *De anima (Of the Soul)*. While Aristotle's observations of plants were less accurate than his observations of animals, his disciple and successor Theophrastus was a keen botanical observer. His treatise *De historia plantarum (Of the History of Plants)* was a pioneering work that made Theophrastus famous as the "father of botany."[25]

In the first century A.D., the Roman naturalist Pliny the Elder (Gaius Plinius) wrote a monumental encyclopedia titled *Natural History*, comprising 37 books in which almost 500 Greek and Roman authors are cited. It became the favorite scientific encyclopedia in the Middle Ages, not only because of its rich content but also because it was written in an informal style. While it lacked scientific rigor, it was much easier and more pleasant to read than the learned volumes of Aristotle and the other Greek philosophers. For most Renaissance humanists, Pliny's name meant natural history itself. And his encyclopedia was the most convenient entry point to further research.

Botany, from ancient times up to the end of the sixteenth century, was often considered a subdiscipline of medicine, since plants were mainly studied for their use in the healing arts. For centuries the authoritative text in this field was the *Materia Medica* by the Greek physician Dioscorides, who was a contemporary of Pliny.

MEDICINE AND ANATOMY

In prehistoric cultures around the world, the origin of illness and the process of healing were associated with forces belonging to the spirit world, and a great variety of healing rituals and practices were developed to deal with illness accordingly.[25] In Western medicine, a revolutionary change occurred in Greece in the fifth century B.C., with the emergence of the scientific medical tradition associated with Hippocrates. There is no doubt that a famous physician by that name practiced and taught medicine around 400 B.C. on the island of Cos, but the voluminous writings attributed to him, known as the Hippocratic Corpus, were probably written by several authors at different times.

At the core of Hippocratic medicine was the conviction that illnesses are not caused by supernatural forces, but are natural phenomena that can be studied scientifically and influenced by therapeutic procedures and wise management of one's life.[26] Thus medicine should be practiced as a scientific discipline and should include the prevention of illness, as well as its diagnosis and treatment. This attitude has formed the basis of scientific medicine to the present day.

Health, according to the Hippocratic writings, requires a state of balance among environmental influences, the way in which we live, and the various components of human nature. One of the most important volumes in the Hippocratic Corpus, the book on *Airs, Waters and Places*, represents what we might now call a treatise on human ecology. It shows in great detail how the well-being of individuals is influenced by environmental factors—the quality of air, water, and food, the topography of the land, and general living habits. During the last two decades of the fifteenth century, this and several other volumes from the Hippocratic Corpus were available to scholars in Latin, most of them derived from Arabic translations.[27]

The culmination of anatomical knowledge in antiquity was reached in the second century A.D. with Galen (Claudius Galenus), a Greek physician who resided chiefly in Rome, where he had a large practice. His work in anatomy and physiology, based partly on dissections of animals, greatly increased the ancient knowledge of the arteries, brain, nerves, and spinal cord. Galen wrote over one hundred treatises in which he summarized and systematized the medical knowledge of his time in accordance with his own theories. By the end of the ninth century, all his works had been translated into Arabic, and Latin translations followed in due course. The authority of the Galenic teachings was unchallenged until Leonardo's time, although they were not founded on detailed knowledge of human organs. His dogmatic doctrines actually impeded medical progress. Nor was Galen successful in correlating his medical theories with corresponding therapies.

The medical bible throughout the Middle Ages and the Renaissance was the *Canon of Medicine*, written by the physician and philosopher Avicenna (Ibn Sina) in the eleventh century. A vast encyclopedia that codified the complete Greek and Arabic medical knowledge, Avicenna's *Canon* was more elaborate than Galen's works and had the advantage of being a single monumental opus rather than a collection dispersed in many separate treatises.

Medical teaching at the great universities was based on the classical texts of Hippocrates, Galen, and Avicenna, and concentrated on interpreting the classics, without questioning them or comparing them with clinical experience. Practicing physicians, on the other hand, many of them without medical degrees, used their own eclectic combinations of therapies.[28] The best of them simply relied on the Hippocratic notions of clean living and the ability of the body to heal itself.

As medical theory and practice increasingly diverged, human anatomy gradually became an independent field of study. Leonardo da Vinci, who became the greatest Renaissance anatomist, never practiced medicine. In fact, Leonardo had a very low opinion of doctors. "Strive to preserve your health," he wrote on a sheet of anatomical drawings, "in which you will be the more successful the more you are wary of physicians."[29]

One of the earliest texts on anatomy was the *Anatomia* by Mondino de' Luzzi, a professor at Bologna in the fourteenth century. He was one of the few medieval teachers who actually performed anatomical dissections himself.[30] His text, much influenced by the Arab interpreters of Galen, gave rudimentary instructions for dissections without, however, specifying the exact position and nature of individual organs. Yet, because of its succinctness and utility, Mondino's *Anatomia* was a standard textbook in medical schools in the fourteenth and fifteenth centuries.

LEONARDO AND THE CLASSICS

During the years of his extensive self-education in Milan,[31] Leonardo familiarized himself with the principal classical texts. He not only accumulated a considerable personal library, but also consulted classical manuscripts in the private libraries of wealthy aristocrats and monasteries whenever he had an opportunity, or borrowed them from other scholars. His Notebooks are full of reminders to himself to borrow or consult certain books. Since he had only the most rudimentary knowledge of Latin, he studied Italian translations whenever he could obtain them, or sought out scholars who could help him with the Latin texts.

We know from Leonardo's own accounts that he knew Plato's *Timaeus* well. He also owned several of Aristotle's works, in particular the *Physics*. His knowledge of the mathematical writings of Plato, Pythagoras, Archimedes, and Euclid was derived mostly from Luca Pacioli's famous Renaissance textbook, which was written in Italian. When Leonardo and Pacioli became friends, Pacioli helped Leonardo deepen his understanding of mathematics, particularly geometry, by guiding him through the complete Latin edition of Euclid's *Elements*.[32]

Leonardo's interest in astronomy was largely confined to studying optical effects in the visual perception of the heavenly bodies. But he was well aware of the Ptolemaic model of planetary motions. He owned several books on astronomy and cartography, including Ptolemy's celebrated *Cosmography* and a work by the Arabian astronomer Albumazar (Abu-Mashar).[33] With regard to natural history, Leonardo, like most Renaissance humanists, was well acquainted with the works of Aristotle, Pliny the Elder, and Dioscorides. He studied an Italian edition of Pliny's encyclopedic *Natural History*, printed in Venice in 1476, and read Dioscorides' popular *Materia Medica*. His own work in botany, however, went far beyond those classical texts.[34]

Many of Leonardo's greatest scientific achievements were in the field of anatomy, and it was this subject that he studied most carefully in the classical texts. He owned an Italian edition of Mondino's *Anatomy* and used it as an initial guide for dissections of the nervous system and other parts of the body. Through Mondino, he became acquainted with the theories of Galen and Avicenna, and subsequently studied an Italian edition of Avicenna's classic *Canon of Medicine*. Eventually Leonardo probably read some of Galen's work in Latin, with the help of the young anatomist Marcantonio della Torre, whom he met during his second period in Milan.[35] Having thoroughly studied the three principal medical authorities of his time—Galen, Avicenna, and Mondino—Leonardo had a solid foundation in classical and medieval anatomy, on which he built his own extraordinary accomplishments.

Leonardo da Vinci shared with his fellow humanists their great confidence in the capabilities of the human individual, their passion for voyages of exploration, and their excitement about the rediscovery of the classical texts of antiquity. But he differed dramatically from most of them by refusing to blindly accept the teachings of the classical authorities. He studied them carefully, but then he tested them by subjecting them to rigorous comparisons with his own experiments and his direct observations of nature. In doing so, I would argue, Leonardo single-handedly developed a new approach to knowledge, known today as the scientific method.