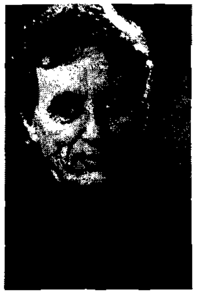
The
Science OF
LEONARDO



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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

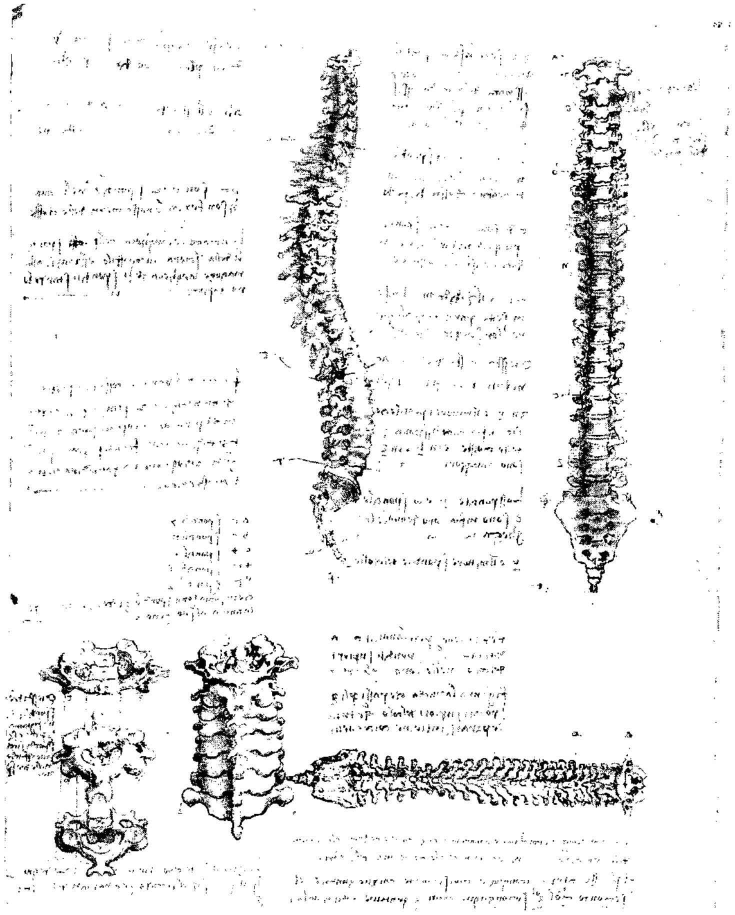

Figure 5-1: The vertebral column, c. 1510, Anatomical Studies, folio 139v

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."

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.

SIX

Science Born of Experience

Today's modern word "science" is derived from the Latin *scientia*, which means "knowledge," a meaning that was retained throughout the Middle Ages and the Renaissance. The modern understanding of science as an organized body of knowledge, acquired through a particular method, evolved gradually during the eighteenth and nineteenth centuries. The characteristics of the scientific method were fully recognized only during the twentieth century and are still frequently misunderstood, especially by the general public.

THE SCIENTIFIC METHOD

The scientific method represents a particular way of gaining knowledge about natural phenomena. First, it involves the systematic observation of the phenomena being studied and the recording of these observations as evidence, or scientific data. In some sciences, such as physics, chemistry, and biology, systematic observation includes conducting controlled experiments; in others, such as astronomy or paleontology, this is not possible.

Next, scientists attempt to interconnect the data in a coherent way, free of internal contradictions. The resulting representation is known as a scientific model. Whenever possible, we try to formulate our models in mathematical language, because of the precision and internal consistency inherent in mathematics. However, in many cases, especially in the social sciences, such attempts have been problematic, as they tend to confine the scientific models to such a narrow range that they lose much of their usefulness. Thus we have come to realize over the last few decades that neither mathematical formulations nor quantitative results are essential components of the scientific method.

Last, the theoretical model is tested by further observations and, if possible, additional experiments. If the model is found to be consistent with all the results of these tests, and especially if it is capable of predicting the results of new experiments, it eventually becomes accepted as a scientific theory. The process of subjecting scientific ideas and models to repeated tests is a collective enterprise of the community of scientists, and the acceptance of the model as a theory is done by tacit or explicit consensus in that community.

In practice, these steps, or stages, are not neatly separated and do not always occur in the same order. For example, a scientist may formulate a preliminary generalization, or hypothesis, based on intuition or initial empirical data. When subsequent observations contradict the hypothesis, the researcher may try to modify the hypothesis without giving it up completely. But if the empirical evidence continues to contradict the hypothesis or the scientific model, the scientist is forced to discard it in favor of a new hypothesis or model, which is then subjected to further tests. Even an accepted theory may eventually be overthrown when contradictory evidence comes to light. This method of basing all models and theories firmly on empirical evidence is the very essence of the scientific approach.

All scientific models and theories are limited and approximate. This realization has become crucial to the contemporary understanding

of science.[1] Twentieth-century science has shown repeatedly that all natural phenomena are ultimately interconnected, and that their essential properties, in fact, derive from their relationships to other things. Hence, in order to explain any one of them completely, we would have to understand all the others, which is obviously impossible. This insight has forced us to abandon the Cartesian belief in the certainty of scientific knowledge and to realize that science can never provide complete and definitive explanations. In science, to put it bluntly, we never deal with truth, in the sense of a precise correspondence between our descriptions and the described phenomena. We always deal with limited and approximate knowledge.

This may sound frustrating, but for many scientists the fact that we *can* formulate approximate models and theories to describe an endless web of interconnected phenomena, and that we are able to systematically improve our models or approximations over time, is a source of confidence and strength. As the great biochemist Louis Pasteur put it, "Science advances through tentative answers to a series of more and more subtle questions which reach deeper and deeper into the essence of natural phenomena."[2]

LEONARDO'S EMPIRICAL APPROACH

Five hundred years before the scientific method was recognized and formally described by philosophers and scientists, Leonardo da Vinci single-handedly developed and practiced its essential characteristics—study of the available literature, systematic observations, experimentation, careful and repeated measurements, the formulation of theoretical models, and frequent attempts at mathematical generalizations.

The full extent of Leonardo's method has come to light only recently with the accurate dating of his notes, which now makes it possible to follow the evolution of his ideas and techniques. For centuries, published selections from his Notebooks were arranged according to subject matter and often presented contradictory statements from different periods of Leonardo's life. But during the last three decades the Notebooks have finally been dated properly.

The critical examination and dating of old manuscripts, known as paleography, has grown into a sophisticated science.[3] In the case of the Notebooks, the dating involves not only evaluating actual dates, references to external events, and various cross-references in the text, but also a meticulous analysis of the evolution of Leonardo's style of writing and drawing over his lifetime; his use of different types of paper (often with distinctive watermarks) and of different kinds of pens, ink, and other writing materials at different times; as well as comparing and piecing together a host of stains, tears, special folds, and all kinds of marks added by various collectors over the centuries.

As a result of this painstaking work, performed for several decades under the leadership of Carlo Pedretti, all of Leonardo's manuscripts are now published in facsimile editions together with carefully transcribed and annotated versions of the original texts. Passages from different periods of Leonardo's life—sometimes even on the same folio of a manuscript—have been dated accurately. These scholarly publications have made it possible to recognize the developments of Leonardo's theoretical models, and the gradual perfection of his methods of observation and representation on the page, and thus to appreciate aspects of his scientific approach that could not be recognized before.[4]

One revolutionary change Leonardo brought to natural philosophy in the fifteenth century was his relentless reliance on direct observation of nature. While the Greek philosophers and scientists had shunned experimentation, and most of the Renaissance humanists uncritically repeated the pronouncements of the classical texts, Leonardo never tired of emphasizing the importance of *sperienza*, the direct experience of natural phenomena. From his earliest entries, when he began his scientific investigations, to his final days, he sprinkled his Notebooks with declarations about the critical importance of methodical observation and experimentation.

"All our knowledge has its origin in the senses," he noted in his first Notebook, the Codex Trivulzianus.[5] "Wisdom is the daughter of experience," we read in the Codex Forster,[6] and in his *Treatise on Painting*, Leonardo asserted: "To me it seems that those sciences are vain and full of errors that are not born of experience, mother of all certainty. . . . that is to say, which do not at their beginning, middle, or end pass through any of the five senses."[7] Such an approach to the study of nature was unheard-of in Leonardo's day, and would fully emerge again only in the seventeenth century, the era of the Scientific Revolution.

Leonardo despised the established philosophers who merely quoted the classical texts in Latin and Greek. "They strut about puffed up and pompous," he wrote scornfully, "decked out and adorned not with their own labors but with those of others."[8] He recognized that learning from skilled masters was important in the arts, but he also observed that such masters were rare. "The surer way," he suggested, "is to go to the objects of nature, rather than those that are imitated with great deterioration, and so acquire sad habits; for he who can go to the well does not go to the water jar."[9]

When he was over sixty and living in Rome, Leonardo, one day, was working on problems of mechanics, filling the pages of a small notebook with a series of elaborate diagrams of scales and pulleys. "I shall now define the nature of composite scales . . . ," he wrote at one point. And then—as if suddenly mindful of future readers who needed to be taught about science—he interrupted himself to add his now famous manifesto on his scientific method:

> But first I shall do some experiments before I proceed farther, because my intention is to cite experience first and then with reasoning show why such experience is bound to operate in such a way. And this is the true rule by which those who speculate about the effects of nature must proceed.[10]

In the intellectual history of Europe, Galileo Galilei, who was born 112 years after Leonardo, is usually credited with being the first to develop this kind of rigorous empirical approach and is often hailed as the "father of modern science." There can be no doubt that this honor would have been bestowed on Leonardo da Vinci had he published his scientific writings during his lifetime, or had his Notebooks been widely studied soon after his death.

The empirical approach came naturally to Leonardo. He was gifted with exceptional powers of observation and a keen visual memory, complemented by his great drawing skills.[11] Art historian Kenneth Clark suggests that Leonardo had an "inhumanly sharp eye with which . . . he followed the movements of birds or of a wave, understood the structure of a seed-pod or skull, noted down the most trivial gesture or most evasive glance."[12]

What turned Leonardo from a painter with exceptional gifts of observation into a scientist was his recognition that his observations, in order to be scientific, needed to be carried out in an organized, methodical fashion. Scientific experiments are performed repeatedly and in varying circumstances so as to eliminate accidental factors and technical flaws as much as possible. The parameters of the experimental setting are varied in order to bring to light the essential unchanging features of the phenomena being investigated. This is exactly what Leonardo did. He never tired of carrying out his experiments and observations again and again, with fierce attention to the minutest details, and he would often vary his parameters systematically to test the consistency of his results. "We can only marvel at the master's voracious appetite for details," wrote art historian Erich Gombrich. "His range of activities and his insatiable thirst for knowledge seem never to have come in conflict with that awe-inspiring power of concentration that made him study one plant, one muscle, one sleeve or indeed one geometrical problem as if nothing else would ever concern him."[13]

In the Notebooks, Leonardo repeatedly commented on how a good experiment should be conducted, and in particular he stressed the need for careful repetitions and variations. Thus we read in Manuscript A: "Before you make a general rule of this case, test it two or three times and observe whether the tests produce the same effects." In Manuscript M he notes: "This experiment should be made several times, so that no accident may occur to hinder or falsify the test."[14]

Being a brilliant inventor and mechanical engineer, Leonardo was able to design ingenious experiments with the simplest means. For example, grains of millet or sprigs of straw, thrown into flowing water, helped him visualize and draw the shapes of the flow lines; specially designed floats, suspended at different depths of a flowing river, allowed him to measure the water's speed at different levels and at different distances from the banks.[15] He built glass chambers with their bases lined with sand and rear walls painted black for observing fine details of water movements in a controlled laboratory setting.[16]

Leonardo had to invent and design most of his measuring instruments. These included a device for measuring wind speed, a hygrometer to measure the humidity of the air, and various types of odometers to record distances traveled. In the course of surveying land, Leonardo would sometimes attach a pendulum to his thigh, which moved the teeth in a cogwheel to count the number of his steps. At other times he would use a cart with a cogwheel, and the cogwheel was designed to advance one cog with every ten *braccia* (about twenty feet) traveled, until a pebble audibly dropped into a metal basin at a distance of one mile.[17] In addition, he made many attempts to improve clock mechanisms for time measurement, which was still in its infancy in his day.[18]

In his scientific observations and experiments, Leonardo showed the same patience and subtle attention to detail that he practiced as a painter. This is especially noticeable in his anatomical research. For example, in one dissection he poured wax into the cavities of the brain known as cerebral ventricles to determine their shape. "Make two vent holes in the horns of the greater ventricles and insert melted wax with the syringe," he noted in his Anatomical Studies. "Then, when the wax has set, dissect off the brain and you will see the shape of the three ventricles exactly."[19] He invented an equally ingenious technique for dissecting the eye. As physician Sherwin Nuland describes it:

> In dissecting the eye, a notoriously difficult organ to cut, Leonardo hit upon the idea of first immersing it in egg white and then boiling the whole, so as to create a coagulum [thickened mass] before cutting into the tissue. Similar embedding techniques are routinely used today to enable accurate slicing of fragile structures.[20]

The systematic approach and careful attention to detail that Leonardo applied to his observations and experiments are characteristic of his entire method of scientific investigation. He would usually start from commonly accepted concepts and explanations, often summarizing what he had gathered from the classical texts before proceeding to verify it with his own observations. Sometimes he jotted down these summaries in the form of quick sketches, or even as elaborate drawings.

Before the accurate dating of the Notebooks, these drawings were often seen as indications of Leonardo's own lack of scientific knowledge rather than as the "citations" of received opinion that they are.

For example, the well-known "coitus figure" in the Windsor Collection of anatomical drawings, which shows the male reproductive organs with anatomies that are mostly erroneous, was long viewed as reflecting Leonardo's poor understanding of anatomy. More recently, however, the drawing was recognized by the historian of medicine and Leonardo scholar Kenneth Keele as Leonardo's illustration of what he had read in Plato's *Timaeus*. He had used it as the starting point for his own anatomical explorations of human reproductive processes.[21]

After testing the traditional ideas repeatedly with careful observations and experiments, Leonardo would either adhere to tradition if he found no contradictory evidence or would formulate his own alternative explanations. Sometimes he would dispense with comments altogether, relying entirely on the persuasive power of his drawings.

Leonardo generally worked on several problems simultaneously and paid special attention to similarities of forms and processes in different areas of investigation—for example, between the forces transmitted by pulleys and levers and those transmitted by muscles, tendons, and bones; between patterns of turbulence in water and in air; between the flow of sap in a plant or tree and the flow of blood in the human body.

When he made progress in his understanding of natural phenomena in one area, he was always aware of the analogies and interconnecting patterns to phenomena in other areas and would revise his theoretical ideas accordingly. This method led him to tackle many problems not just once but several times during different periods of his life, modifying his theories in successive steps as his scientific thought evolved over his lifetime.

Leonardo's method of repeatedly reassessing his theoretical ideas in various areas meant that he never saw any of his explanations as "final." Even though he believed in the certainty of scientific knowledge, as did most philosophers and scientists for the next three hundred years, his successive theoretical formulations in many fields are quite similar to the theoretical models that are characteristic of modern science. For example, he proposed several different models for the functioning of the heart and its role in maintaining the flow of blood, including one that pictured the heart as a stove housing a central fire, before he concluded that the heart is a muscle pumping blood through the arteries.[22] Leonardo also used simplified models—or approximations, as we would say today—to analyze the essential features of complex natural phenomena. For instance, he represented the flow of water through a channel of varying cross sections by using a model of rows of men marching through a street of varying width.[23]

Like modern scientists, Leonardo was always ready to revise his models when he felt that new observations or insights required him to do so. In his art as in his science, he always seemed to be more interested in the process of exploration than in the completed work or final results. Thus many of his paintings and all of his science remained unfinished work in progress.

This is a general characteristic of the modern scientific method. Although scientists publish their work in various stages of completion in papers, monographs, and textbooks, science as a whole is always work in progress. Old models and theories continue to be replaced by new ones, which are judged superior but are nevertheless limited and approximate, destined to be replaced in their turn as knowledge progresses.

Since the Scientific Revolution in the seventeenth century, this progress in science has been a collective enterprise. Scientists continually exchanged letters, papers, and books, and discussed their theories at various gatherings. This continual exchange of ideas is well documented and thus makes it fairly easy for historians to follow the progress of science through the centuries. With Leonardo, the situation is quite different. He worked alone and in secrecy, did not publish any of his findings, and only rarely dated his notes. In addition, he frequently copied excerpts from scholarly works into his Notebooks without proper attribution, even without identifying them as quotations, so that historians long took some of those copied passages for Leonardo's own original ideas.

Having pioneered the scientific method in solitude, Leonardo did not see science as a collective, collaborative enterprise. During his lifetime, therefore, any progress in his science was evident to him alone. Scholars today have had to engage in meticulous detective work to reconstruct the evolution of his scientific thought.

THE NOTEBOOKS

Leonardo recorded the results of his observations and experiments, his theoretical models, and his philosophical speculations in thousands of pages of notes, some in the form of well-organized treatises in various stages of completion, but most of them as disjointed notes and drawings without any apparent order, sometimes scribbled on the same folio at different times. Even though scholarly editions with clear transcriptions of all the Notebooks are now available, and most of the pages have been carefully dated, Leonardo's notes and drawings are so extensive, and their topics so diverse, that much work remains to be done to fully analyze their scientific contents and evaluate their significance.

The original text is difficult to read not only because it is written in mirror writing and is often disjointed, but also because Leonardo's spelling and syntax are highly idiosyncratic. He always seems to be in a hurry to jot down his thoughts, makes plenty of banal slips and errors, and often strings words together without any spaces between them. Punctuation is practically absent in his handwriting. The period (the only punctuation he uses) may occur very frequently in some manuscripts and be totally absent in others. In addition, like anyone used to taking regular and extensive personal notes, he employs his own code of abbreviations and shorthand notations.

In the fifteenth century, standard Italian spelling had not yet been established,[24] and scribes allowed themselves considerable variations. Accordingly, Leonardo varies his spellings quite indiscriminately, recording the sound of the spoken word in his own idiosyncratic ways rather than following any written tradition.

Taken together, these idiosyncrasies present considerable obstacles to the reader of Leonardo's original text. Fortunately, however, scholars have provided us with two kinds of transcriptions which, reproduced side by side, solve all these problems while following Leonardo's words

Figure 6-1: Spiraling foliage of Star of Bethlehem, c. 1508, Windsor Collection, Landscapes, Plants, and Water Studies, folio 16r

as closely as possible.[25] The so-called "diplomatic" transcription gives a printed version of the text exactly the way Leonardo wrote it, with all the abbreviations, idiosyncratic spellings, errors, crossed-out words, and other anomalies. The "critical" transcription next to it is a cleaned-up version of the text in which the abbreviations and errors have been eliminated, and Leonardo's archaic and erratic spellings have been replaced by their modern Italian counterparts, including modern punctuation, whenever this could be done without affecting the original Florentine pronunciation.

From these critical transcriptions emerges a flowing text, liberated from the obstacles mentioned, which anybody who is reasonably fluent in Italian can read without too many difficulties. Such reading makes it evident that Leonardo's language is highly eloquent, often witty, and at times movingly beautiful and poetic. It is worth reading his writings aloud to appreciate their beauty, because Leonardo's medium was the spoken word rather than the carefully composed written text. To make his arguments, he used the persuasive power of his drawings as well as the elegant cadences of his native Tuscan.

Let me now turn to the key characteristics of the science Leonardo discussed and developed in his Notebooks.

A SCIENCE OF LIVING FORMS

From the very beginning of Western philosophy and science, there has been a tension between mechanism and holism, between the study of matter (or substance, structure, quantity) and the study of form (or pattern, order, quality).[26] The study of matter was championed by Democritus, Galileo, Descartes, and Newton; the study of form by Pythagoras, Aristotle, Kant, and Goethe. Leonardo followed the tradition of Pythagoras and Aristotle, and he combined it with his rigorous empirical method to formulate a science of living forms, their patterns of organization, and their processes of growth and transformation. He was deeply aware of the fundamental interconnectedness of all phenomena and of the interdependence and mutual generation of all parts of an organic whole, which Immanuel Kant in the eighteenth century would define as "self-organization."[27] In the Codex Atlanticus, Leonardo eloquently summarized his profound understanding of life's basic processes by paraphrasing a statement by the Ionian philosopher Anaxagoras: "Everything comes from everything, and everything is made of everything, and everything turns into everything, because that which exists in the elements is made up of these elements."[28]

The Scientific Revolution replaced the Aristotelian worldview with the concept of the world as a machine. From then on the mechanistic approach—the study of matter, quantities, and constituents—dominated Western science. Only in the twentieth century did the limits of Newtonian science become fully apparent, and the mechanistic Cartesian worldview begin to give way to a holistic and ecological view not unlike that developed by Leonardo da Vinci.[29] With the rise of systemic thinking and its emphasis on networks, complexity, and patterns of organization, we can now more fully appreciate the power of Leonardo's science and its relevance for our modern era.

Leonardo's science is a science of qualities, of shapes and proportions, rather than absolute quantities. He preferred to *depict* the forms of nature in his drawings rather than *describe* their shapes, and he analyzed them in terms of their proportions rather than measured quantities. Proportion was seen by Renaissance artists as the essence of harmony and beauty. Leonardo filled many pages of his Notebooks with elaborate diagrams of proportions between the various parts of the human figure, and he drew corresponding diagrams to analyze the body of the horse.[30] He was far less interested in absolute measurements, which, in any case, were not as accurate, nor as important, in his time as they are in the modern world. For example, the standard units of length and weight—the *braccio* (arm) and the pound—both varied in different Italian cities from Florence to Milan to Rome, and they had different values in neighboring European countries.[31]

Leonardo was always impressed by the great diversity and variety of living forms. "Nature is so delightful and abundant in its variations," he wrote in a passage about how to paint trees, "that among trees of the same kind there would not be found one plant that resembles another nearby, and this is so not only of the plant as a whole, but among the branches, the leaves, and the fruit, not one will be found that looks precisely like another."[32]

Leonardo recognized this infinite variety as a key characteristic of living forms, but he also tried to classify the shapes he studied into different types.

Figure 6-2: Flow of water and flow of human hair, c. 1513, Windsor Collection, Landscapes, Plants, and Water Studies, folio 48r

He made lists of different body parts, such as lips and noses, and identified different types of human figures, varieties of plant species, and even classes of water vortices.[33] Whenever he observed natural forms, he recorded their essential features in drawings and diagrams, classified them into types if possible, and tried to understand the processes and forces underlying their formation.

In addition to the variations within a particular species, Leonardo paid attention to similarities of organic forms in different species and to similarities of patterns in different natural phenomena. The Notebooks contain countless drawings of such patterns—anatomical similarities between the leg of a man and that of a horse, spiraling whirlpools and spiraling foliages of certain plants (Fig. 6-1), the flow of water and the flow of human hair (Fig. 6-2), and so on. On a folio of anatomical drawings, he notes that the veins in the human body behave like oranges, "in which, as the skin thickens, so the pulp diminishes the older they become."[34] Among his studies for *The Battle of Anghiari*, we find a comparison of expressions of fury in the faces of a man, a horse, and a lion (Fig. 6-3).

These frequent comparisons of forms and patterns are usually described as analogies by art historians, who point out that explanations in terms of analogies were common among artists and philosophers in the Middle Ages and the Renaissance.[35] This is certainly true. But Leonardo's comparisons of organic forms and processes in different species are much more than simple analogies. When he investigates similarities between the skeletons of different vertebrates, he studies what biologists today call homologies—structural correspondences between different species, due to their evolutionary descent from a common ancestor.

The similarities of expressions of fury in the faces of animals and humans are homologies as well, derived from commonalities in the evolution of face muscles. Leonardo's analogy between the skin of human veins and the skin of oranges during the process of aging is based on the fact that in both cases he was observing the behavior of living tissues. In all these cases, he realized intuitively that living forms in different species exhibit similarities of patterns. Today we explain these patterns in terms of microscopic cellular structures and of metabolic and evolutionary processes. Leonardo, of course, did not have access to those levels of explanation, but he correctly perceived that throughout the creation (or evolution, as we would say today) of the great diversity of forms, nature used again and again the same basic patterns of organization.

Leonardo's science is utterly dynamic. He portrays nature's forms—in mountains, rivers, plants, and the human body—in ceaseless movement and transformation.

Form, for him, is never static. He realizes that living forms are continually being shaped and transformed by underlying processes. He studies the multiple ways in which rocks and mountains are shaped by turbulent flows of water, and how the organic forms of plants, animals, and the human body are shaped by their metabolism. The world Leonardo portrays, both in his art and in his science, is a world in de-

Figure 6-3: Fury in the faces of a man, a horse, and a lion, c. 1503–4, Windsor Collection, Horses and Other Animals, folio 117r

velopment and flux, in which all configurations and forms are merely stages in a continual process of transformation. "This feeling of movement inherent in the world," writes art historian Daniel Arasse, "is absolutely central to Leonardo's work, because it reveals an essential aspect of his genius, thereby defining his uniqueness among his contemporaries."[36] At the same time, Leonardo's dynamic understanding

of organic forms reveals many fascinating parallels to the new systemic understanding of life that has emerged at the forefront of science over the past twenty-five years.

In Leonardo's science of living forms, life's patterns of organization and its fundamental processes of metabolism and growth were the unifying conceptual threads that interlinked his knowledge of macro- and microcosm. In the macrocosm, the main themes of his science were the movements of water and air, the geological forms and transformations of the Earth, and the botanical diversity and growth patterns of plants. In the microcosm, his main focus was on the human body—its beauty and proportions, the mechanics of its movements, and how it compared to other animal bodies in motion, in particular birds in flight.

THE MOVEMENTS OF WATER

Leonardo was fascinated by water in all its manifestations. He recognized its fundamental role as life's medium and vital fluid, as the matrix of all organic forms. "It is the expansion and humor of all living bodies," he wrote. "Without it nothing retains its original form."[37] Throughout his life, he strove to understand the mysterious processes underlying the creation of nature's forms by studying the movements of water through earth and air.

As an engineer, Leonardo worked extensively on schemes of canalization, irrigation, the drainage of marshes, and the uses of waterpower for pumping, milling, and sawing. Like other noted engineers in the Renaissance, he was very familiar with the beneficial as well as the destructive effects of the power of water. But he was the only one to go beyond empirical rules of hydraulic engineering and embark on sustained theoretical studies of the flow of water. His examinations and exquisite drawings of the flows of rivers, eddies, spiraling vortices, and other patterns of turbulence establish Leonardo as a pioneer in a field that did not even exist in his time—the discipline known today as fluid dynamics.

Throughout his life, Leonardo observed the flows of rivers and tides, drew beautiful and accurate maps of entire watersheds, and investigated currents in lakes and seas, flows over weirs and waterfalls, and the movement of waves as well as flows through pipes, nozzles, and orifices. His observations, drawings, and theoretical ideas would fill hundreds of pages in his Notebooks.

Through this lifelong study, Leonardo gained a full understanding of the main characteristics of fluid flow. He recognized the two principal forces operating in flowing water—the force of gravity and the fluid's internal friction, or viscosity—and he correctly described many phenomena generated by their interplay. He also realized that water is incompressible and that, even though it assumes an infinite number of shapes, its mass is always conserved.

In a branch of science that did not even exist before him, Leonardo's deep insights into the nature of fluid flow must be ranked as a momentous achievement. That he also drew many turbulent structures erroneously and imagined some flow phenomena that do not occur in reality does not diminish his great accomplishments, especially in view of the fact that even today scientists and mathematicians encounter considerable difficulties in their attempts to predict and model the complex details of turbulent flows.

At the center of Leonardo's investigations of turbulence lies the water vortex, or whirlpool. Throughout the Notebooks, there are countless drawings of eddies and whirlpools of all sizes and types—in the currents of rivers and lakes, behind piers and jetties, in the basins of waterfalls, and behind objects of various shapes immersed in flowing water. These often very beautiful drawings are testimony to Leonardo's endless fascination with the ever-changing and yet stable nature of this fundamental type of turbulence. I believe that this fascination came from a deep intuition that the dynamics of vortices, combining stability and change, embody an essential characteristic of living forms.[38]

Leonardo was the first to understand the detailed motions of water vortices, often drawing them accurately even in complex situations. He correctly distinguished between flat circular eddies in which the water essentially rotates as a solid body, and spiral vortices (such as the whirlpool in a bathtub) that form a hollow space, or funnel, at their center. "The spiral or rotary movement of every liquid," he noted, "is so much swifter as it is nearer to the center of its revolution. What we are here proposing is a fact worthy of admiration, since the circular movement of the wheel is so much slower as it is nearer to the center of the rotating object."[39] Such detailed studies of vortices in turbulent water were not taken up again for another 350 years, until the physicist Hermann von Helmholtz developed a mathematical analysis of vortex motion in the mid-nineteenth century.

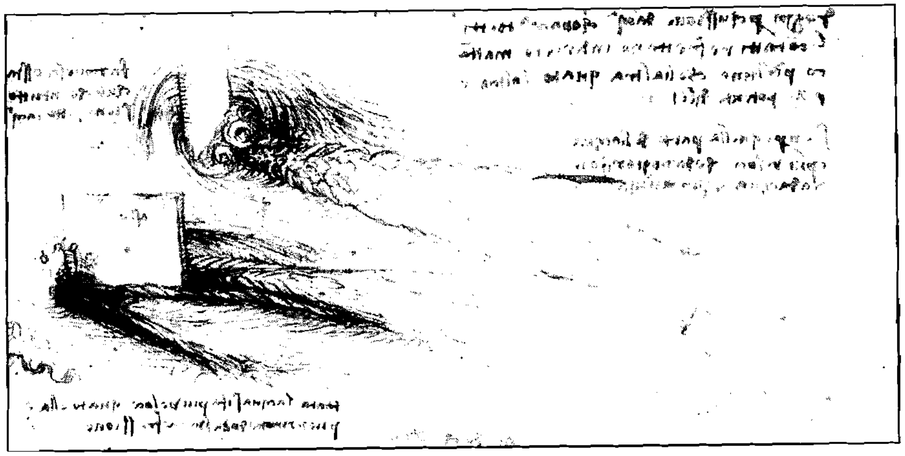

Figure 6-4: Turbulent wakes behind a rectangular plank, c. 1509–11, Windsor Collection, Landscapes, Plants, and Water Studies, folio 42r

Leonardo produced several elaborate drawings of highly complex patterns of turbulence, generated by placing various obstacles into flowing water. Figure 6-4, from the Windsor Collection, shows the turbulent flows around a rectangular plank inserted at two different angles. (Additional variations are suggested in the small sketches to the right of the main drawing.) The upper drawing clearly shows a pair of counter-rotating vortices at the head of a stream of random wake. The essential details of this complex pattern of turbulence are completely accurate—an amazing testimony to Leonardo's powers of observation and conceptual clarity.

THE FORMS AND TRANSFORMATIONS OF THE LIVING EARTH

Leonardo saw water as the chief agent in the formation of the Earth's surface. "Water wears away the mountains and fills up the valleys," he wrote, "and if it could, it would like to reduce the Earth to a perfect sphere."[40] This awareness of the continual interaction of water and rocks impelled him to undertake extensive studies in geology, which informed the fantastic rock formations that appear so often in the shadowy backgrounds of his paintings.

His geological observations are stunning not only by their great accuracy, but also because they led him to formulate general principles that were rediscovered only centuries later and are still used by geologists today.[41] Leonardo recognized temporal sequences in the strata of soil and rock, and corresponding sequences in the fossils deposited in those strata, and he recorded many fine details concerning erosion and deposits by rivers.

He was the first to postulate that the forms of the Earth are the result of processes taking place over long epochs of what we now call geological time. With this view he came close to an evolutionary perspective more than three hundred years before Charles Darwin, who also found inspiration for evolutionary thought in geology. For Leonardo, geological time began with the formation of the living Earth, a process to which he alluded in his paintings with a sense of awe and mystery.

"Describe a landscape with wind and water," Leonardo exhorted his fellow painters, "and at the setting and rising of the sun."[42] He was a true master in rendering these atmospheric effects. Like his predecessors and contemporaries, he frequently introduced flowers and herbs into his paintings for their symbolic meanings, but unlike most of his fellow painters, he was always careful to present plants in their proper ecological habitats with seasonal appropriateness and great botanical accuracy.[43]

The Notebooks contain numerous drawings of trees and flowering plants indigenous to Italy, many of them masterpieces of detailed botanical imagery. Most of these drawings were made as studies for paintings, but some also include detailed notes explaining the plants' characteristics. Unlike the formal decorative plant motifs that were common in Renaissance paintings, Leonardo's flowers, herbs, and trees display a vitality and grace that could only be achieved by a painter who had profound botanical and ecological knowledge.

Indeed, Leonardo's mind was not satisfied with merely depicting plants in paintings, but turned to a genuine inquiry into their intrinsic nature—the patterns of metabolism and growth that underlie their organic forms. He made detailed observations of the effects of sunlight, water, and gravity on plant growth; he examined the sap of trees and discovered that a tree's age could be determined from the number of rings in the cross-section of its trunk; he investigated patterns of leaves and branches around their stems, known to botanists today as the study of phyllotaxis; and he related patterns of branching to the activity of a tree's "humor"—an extraordinary insight into effects of hormonal activity that became known only in the twentieth century. As in so many other fields, Leonardo carried his scientific thinking far beyond that of his peers, establishing himself as the first great theorist in botany.[44]

MACRO- AND MICROCOSM

Whenever Leonardo explored the forms of nature in the macrocosm, he also looked for similarities of patterns and processes in the human body. In so doing, he went beyond the general analogies between macro- and microcosm that were common knowledge in his time, drawing parallels between very sophisticated observations in both realms. He applied his knowledge of turbulent flows of water to the movement of blood in the heart and aorta.[45] He saw the "vital sap" of plants as their essential life fluid and observed that it nourishes the plant tissues, as the blood nourishes the tissues of the human body. He noticed the structural similarity between the stalk (known to botanists as the funiculus) that attaches the seed of a plant to the tissues of the fruit, and the umbilical cord that attaches the human fetus to the placenta.[46] He took these observations as compelling testimonies to the unity of life at all scales of nature.

Leonardo's wide-ranging and meticulous observations of the human body must be ranked among his greatest scientific achievements. In order to study the organic forms of the human body, he dissected numerous corpses of humans and animals, and examined their bones, joints, muscles, and nerves, drawing them with an accuracy and clarity never seen before. At the same time, his anatomical drawings are superb works of art, due to his unique ability to represent forms and movements in stunning visual perspective with subtle gradations of light and shade, which gives his drawings a vivid quality rarely achieved in modern anatomical illustrations.

Looking through Leonardo's drawings and notes in over a thousand pages of anatomical manuscripts, we can discern several broad themes. The first is that of beauty and proportion, which held great fascination for Renaissance artists. They saw proportion in painting, sculpture, and architecture as the essence of harmony and beauty, and there were many attempts to establish a canon of proportions for the human figure. Leonardo threw himself into this project with his usual vigor and attention to detail, taking a wealth of measurements to establish a comprehensive system of correspondences between all parts of the body. At the same time, he explored the relationship between proportion and beauty in his paintings. "The beautiful proportions of an angelic face in painting," he wrote, "produce a harmonious concord, which reaches the eye simultaneously, just as [a chord in] music affects the ear."[47]

The second grand theme of Leonardo's anatomical research was the human body in motion. As noted earlier, Leonardo's science of living forms is a science of movement and transformation, whether he studied mountains, rivers, plants, or the human body. Hence, to understand the human form meant for him to understand the body in motion. He demonstrated in countless elaborate and stunning drawings how nerves, muscles, tendons, and bones work together to move the body.

NATURE'S MECHANICAL INSTRUMENTS

Leonardo never thought of the human body as a machine.[48] However, he clearly recognized that the anatomies of animals and humans involve mechanical functions. In his anatomical drawings, he sometimes replaced muscles by threads or wires to better demonstrate the directions of their forces (see Fig. I-1 on p. 10, and Fig. 9-4 on p. 251). He showed how joints operate like hinges and applied the principle of levers to explain the movements of the limbs. "Nature cannot give movement to animals without mechanical instruments," he declared.[49] Hence, he felt that, in order to understand the movements of the animal body, he needed to explore the laws of mechanics. Indeed, for Leonardo, this was the principal role of this branch of science: "The instrumental or mechanical science is very noble and most useful above all others, because by means of it all animated bodies that have movement perform all their operations."[50]

To investigate the mechanics of muscles, tendons, and bones, Leonardo immersed himself in a long study of the "science of weights," known today as statics, which is concerned with the analysis of loads and forces on physical systems in static equilibrium, such as balances, levers, and pulleys. In the Renaissance this knowledge was very important for architects and engineers, as it is today, and the medieval science of weights comprised a large collection of works compiled in the late thirteenth and the fourteenth centuries.

In his usual fashion, Leonardo absorbed the key ideas from the best and most original texts, commented on many of their postulates in his Notebooks, verified them experimentally, and refuted some incorrect proofs.[51] The classical law of the lever, in particular, appears repeatedly in the Notebooks. In the Codex Atlanticus, for example, Leonardo states, "The ratio of the weights that hold the arms of the balance parallel to the horizon is the same as that of the arms, but it is inverse."[52]

Leonardo applied this law to calculate the forces and weights necessary to establish equilibria in numerous simple and compound systems involving balances, levers, pulleys, and beams hanging from cords.[53] In addition, he carefully analyzed the tensions in various segments of the cords, probably for the purpose of estimating similar tensions in the muscles and tendons of human limbs.

Leonardo applied the lever law not only to situations where the forces act in a direction perpendicular to the lever arms, but also to forces acting at various angles. The Codex Arundel and Manuscript E in particular contain numerous diagrams of varying complexities, with weights exerting forces at different angles via cords and pulleys. He recognized that in such cases, the relevant length in the lever law is not the actual length of the lever arm, but the perpendicular distance from the line of the force to the axis of rotation. He called that distance the "potential lever arm" *(braccio potenziale)* and marked it clearly in many diagrams. In modern statics, the potential lever arm is known as the "moment arm," and the product of moment arm and force is called the "moment," or "torque." Leonardo's discovery of the principle that the sum of the moments about any point must be zero for a system to be in static equilibrium was his most original contribution to statics. It went well beyond the medieval science of weights of his time.

LEONARDO'S MACHINES

Leonardo applied his knowledge of mechanics not only to his investigations of the movements of the human body, but also to his studies of machines. Indeed, the uniqueness of his genius lay in his synthesis of art, science, and design.[54] In his lifetime, he was famous as an artist, and also as a brilliant mechanical engineer who invented and designed countless machines and mechanical devices, often involving innovations that were centuries ahead of his time.[55] Today, Leonardo's technical drawings are frequently exhibited around the world, often supplemented by wooden models that show in impressive detail how the machines work as Leonardo had intended.[56]

As noted earlier, Leonardo was the first to separate individual mechanisms from the machines in which they were embedded.[57] In these studies, he always insisted that any improvement of existing devices must be based on sound knowledge of the principles of mechanics. He paid special attention to the transmission of power and motion from one plane into another, which was a major challenge of Renaissance engineering. In his design of a water-powered milling machine (Fig. 8-3 on p. 218), for example, the motion is transmitted three times between horizontal and vertical axes with the help of a combination of toothed wheels and worm gears. The corresponding transfer of power is clearly indicated by Leonardo in a small diagram below the main drawing.[58]

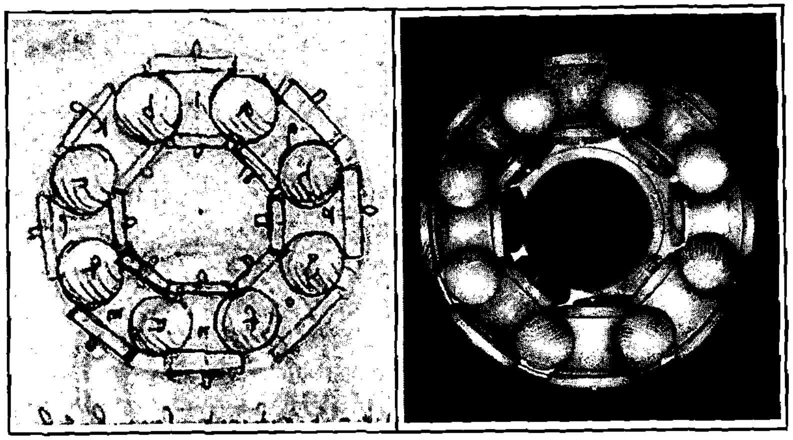

Figure 6-5: Rotary ball bearing, Codex Madrid I, folio 20v; model by Muséo Techni, Montreal, 1987

Among Leonardo's many mechanical innovations, there are several involving the conversion of the rotary motion of a crank into a straight back-and-forth movement, which could be used, for example, in automatic manufacturing processes.[59] And then there is Leonardo's well-known, highly ingenious design of a two-wheeled hoist (Fig. 2-3 on p. 41), which performs the opposite conversion: The motion of a vertical operating lever rocking back and forth is converted into the smooth hoisting of a heavy load by means of two toothed wheels and a caged lantern gear. This is one of Leonardo's most famous technical drawings. It displays the mechanism both in its assembled form and in an exploded view that exposes the complex combination of gears and plates.[60]

In the Renaissance, hoists, cranes, and other large machines were made of wood, and friction between their movable parts was a major problem. Leonardo invented numerous sophisticated devices for reducing friction and wear, including automatic lubrication systems, adjustable bearings, and mobile rollers of various shapes—spheres, cylinders, truncated cones, and the like. Figure 6-5 shows an elegant example of a rotary bearing composed of eight concave-sided spindles rotating on their own axes, interspersed by balls that can rotate freely but are prevented from lateral movements by the spindles. When a platform is put on this ball bearing, friction is reduced to such an extent that the platform can be turned easily even when carrying a heavy load.

All the great Renaissance engineers were aware of the effects of friction, but Leonardo was the only one who undertook systematic empirical studies of frictional forces. He found by experiment that, when an object slides against a surface, the amount of friction is determined by three factors: the roughness of the surfaces, the weight of the object, and the slope of an inclined plane:

> In order to know accurately the quantity of the weight required to move a hundred pounds over a sloping road, one must know the nature of the contact which this weight has with the surface on which it rubs in its movement, because different bodies have different frictions. . . .
>
> Different slopes make different degrees of resistance at their contact; because, if the weight that must be moved is upon level ground and has to be dragged, it undoubtedly will be in the first strength of resistance, because everything rests on the earth and nothing on the cord that must move it. . . . But you know that, if one were to draw it straight up, slightly grazing and touching a perpendicular wall, the weight is almost entirely on the cord that draws it, and only very little rests upon the wall where it rubs.[61]

Leonardo's conclusions are fully borne out by modern mechanics. Today the force of friction is defined as the product of the frictional coefficient (measuring the roughness of the surfaces) and the force perpendicular to the contact surface (which depends both on the object's weight and the slope of the surface).

Leonardo's studies of power transmission led him to investigate the medieval belief that power could be harnessed through perpetual motion machines. At first he accepted this idea. He designed a host of complex mechanisms to keep water in perpetual motion by means of various feedback systems. But eventually he realized that any mechanical system will gradually lose its power because of friction. In the end, Leonardo scoffed at attempts to build perpetual motion machines. "I have found among the excessive and impossible delusions of men," he wrote in the Codex Madrid, "the search for continuous motion, which is called by some the perpetual wheel."[62]

Leonardo extended his keen interest in friction to his extensive studies of fluid flows. The Codex Madrid contains meticulous records of his investigations and analyses of the resistance of water and air to moving solid bodies, as well as of water and fire moving in air.[63] Well aware of the internal friction of fluids, known as viscosity, Leonardo dedicated numerous pages in the Notebooks to analyzing its effects on fluid flow. "Water has always a cohesion in itself," he wrote in the Codex Leicester, "and this is the more potent as the water is more viscous."[64]

Air resistance was of special interest to Leonardo, because it played an important role in one of his great passions—the flight of birds and the design of flying machines. "In order to give the true science of the movement of birds in the air," he declared, "it is necessary first to give the science of the winds."[65]

THE DREAM OF FLYING

The dream of flying like a bird is as old as humanity itself. But nobody pursued it with more intensity, perseverance, and commitment to meticulous research than Leonardo da Vinci. His "science of flight" involved numerous disciplines—from fluid dynamics to human anatomy, mechanics, the anatomy of birds, and mechanical engineering. He diligently pursued these studies throughout most of his life, from the early years of his apprenticeship in Florence to his old age in Rome.[66]

The first intense period of research on flying machines began in the early 1490s, about a decade after Leonardo's arrival in Milan.[67] His experiments during this period combined mechanics and the anatomy of the human body. He carefully investigated and measured the body's ability to generate various amounts of force in order to find out how a human pilot might be able to lift a flying machine off the ground by flapping its mechanical wings.

Leonardo realized that the air under a bird's wing is compressed by

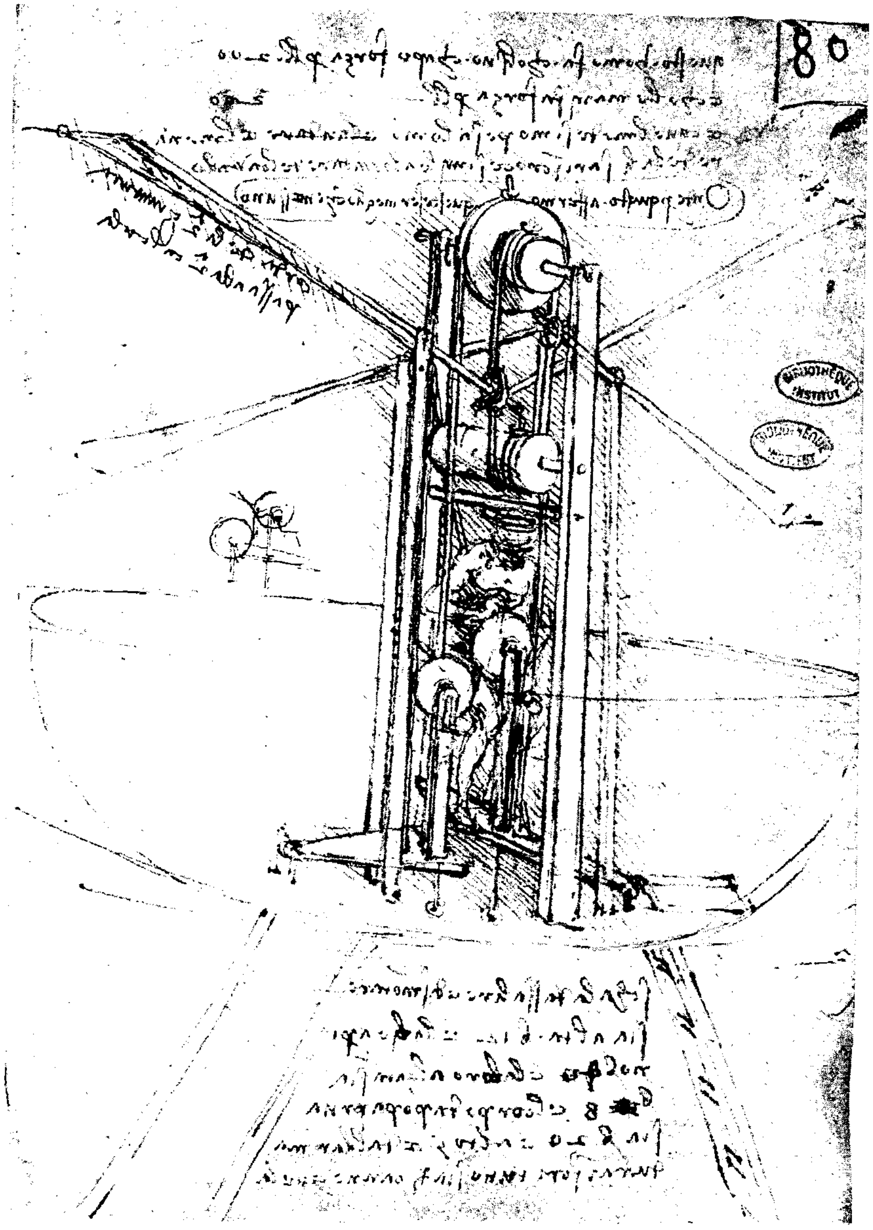

Figure 6-6: Leonardo's "flying ship," Ms. B, folio 80r

the downstroke. "See how the wings, striking against the air, sustain the heavy eagle in the thin air on high," he noted in the Codex Atlanticus, and then he added a remarkable observation: "As much force is exerted by the object against the air as by the air against the object."[68] Leonardo's observation was restated by Isaac Newton two hundred years later and has since been known as Newton's third law of motion.[69]

The result of these investigations was Leonardo's so-called flying ship, his first design of a flying machine (see Fig. 6-6). From the human point of view, the design is rather strange. Crouched down in the center of the craft, the pilot generates the necessary force by pushing two pedals with his feet while simultaneously turning two handles with his hands. As historian Domenico Laurenza points out, "There is no note, no mention to be found . . . of how the pilot will steer the machine in flight; he becomes almost an automatic pilot: he simply has to generate the force to lift off the ground."[70]

During these years, Leonardo designed a series of much more realistic flying machines in which the pilot is placed horizontally (see Fig. 6-7). These designs involve more varied and subtle movements. Human arms and legs are used to make the wings flap. Other movements turn the wings, angling them in the upstroke and opening them to the air in the downstroke, as birds do when flapping in flight. Yet other movements are used to maintain balance and change direction.

These drawings (in Manuscript B and the Codex Atlanticus) represent Leonardo's most sophisticated designs of flying machines. They became the basis of several models built by modern engineers.[71] Figure 6-8 shows one of these models, built from materials that were available in the Renaissance. Unfortunately, the limitations of these materials—wooden struts, leather joints and thongs, and skin of strong cloth—make it evident why Leonardo could not create a viable model of his flying machines, even though they were based on sound aerodynamic principles. The combined weight of the machine and its pilot was simply far too heavy to be lifted by human muscle power.

Eventually, Leonardo became aware that he could not achieve the required power-to-weight ratio for successful flight. Ten years after his experiments with flying machines in Milan, he entered into another in-

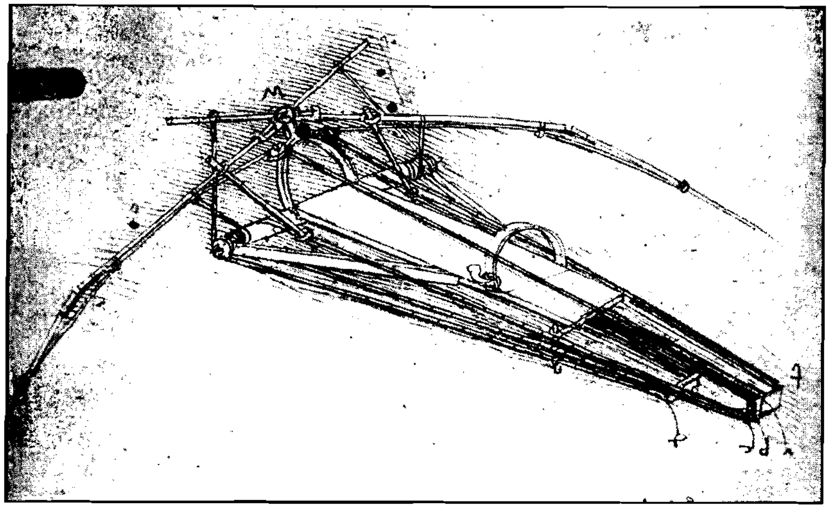

Figure 6-7: Design for flying machine, Ms. B, folio 74v

tense period of research in Florence, which involved his making careful and methodical observations of birds in flight, down to the finest anatomical and aerodynamic details.[72]

In the resulting Notebook, Codex on the Flight of Birds, Leonardo concludes that human flight with mechanical wings might not be possible because of the limitations of our anatomy. Birds have powerful pectoral muscles, he notes, that allow them to flee rapidly from predators, or to carry heavy prey, but they need only a fraction of that force to sustain themselves in the air during normal flight.[73]

His observations led Leonardo to speculate that, even though human beings would not be able to fly by flapping mechanical wings, "soaring flight," or gliding, might be possible, since this required much less force. During his last years in Florence he began to experiment with designs of flying machines that had fixed wings, not unlike a modern hang glider.

Based on these designs, British engineers recently built a glider and tested it successfully in a flight from the chalk cliffs in southeast England known as the Sussex Downs. This maiden flight of "Leonardo's glider," reportedly, exceeded the first attempts by the Wright brothers in 1900.[74]

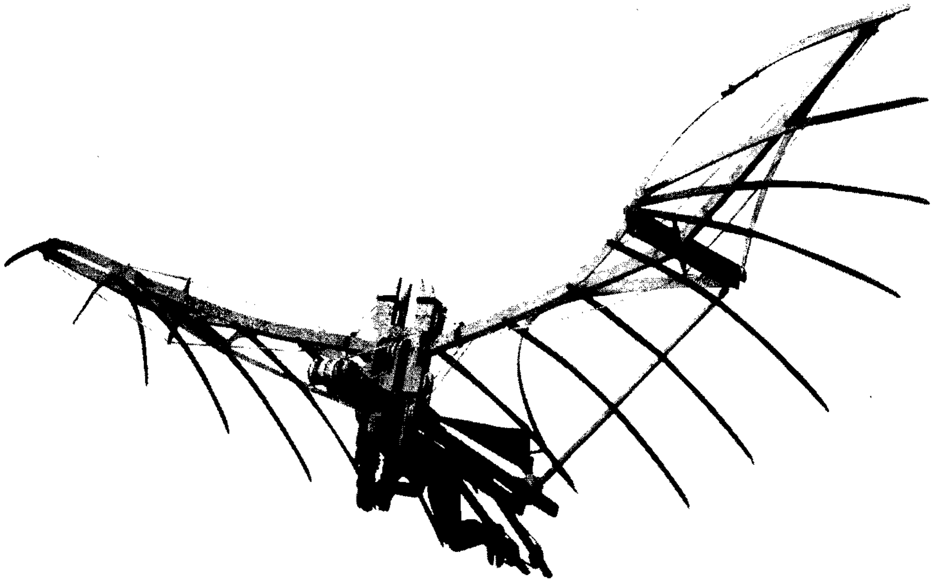

Figure 6-8: Working model of the flying machine, Museum of the History of Science, Florence

Although the machines with movable mechanical wings were not destined to fly, the models built from Leonardo's designs are extraordinary testimonies to his genius as a scientist and engineer. In the words of art historian Martin Kemp: "Using mechanical systems, the wings flap with much of the sinuous and menacing grace of a gigantic bird of prey. . . . [Leonardo's] designs retain their conceptual power as archetypal expressions of man's desire to emulate the birds, and remain capable of inspiring a sense of wonder even in a modern audience, for whom the sight of tons of metal flying through the air has become a matter of routine."[75]

THE MYSTERY OF HUMAN LIFE

The third grand theme in Leonardo's anatomical research (in addition to the themes of harmony and proportion, and the body in motion) is his persistent quest for understanding the nature of life. It is the leitmotiv of his anatomies of the body's internal organs, and in particular of his investigations of the heart—the bodily organ that has served as the foremost symbol of human existence and emotional life throughout the ages.

Leonardo's careful and patient studies of the movements of the heart and the flow of blood, undertaken in old age, are the culmination of his anatomical work. He not only understood and pictured the heart like no one before him, but also observed subtleties in its actions and in the flow of blood that would elude medical researchers for centuries.

Because he did not see the body as a machine, Leonardo's main concern was not the mechanical transportation of blood, but the twin problems, as he saw them, of how the actions of the heart maintained the blood at body temperature and how they produced the "vital spirits" that keep us alive. He accepted the ancient notion that these vital spirits arise from a mixture of blood and air—which is essentially correct, if we identify them with oxygenated blood—and he developed an ingenious theory to solve both problems.

In the absence of any knowledge of chemistry, Leonardo used his extensive understanding of turbulent flows of water and air, and of the role of friction, in his attempt to explain the origin of both the blood-air mixture and the body temperature. This included a meticulous description of many subtle features of blood flow—including the coordinated actions of the heart's four chambers (when all his contemporaries knew only of two), and the corresponding synchronized actions of the coronary valves—which he pictured in a series of superb drawings. According to the eminent physician and Leonardo scholar Kenneth Keele:

> Leonardo's success in cardiac anatomy [is] so great that there are aspects of the work which are not yet equaled by modern anatomical illustration. . . . His consistent practice of illustration of the heart and its valves, both in systole and in diastole, with a comparison of the position of the parts, has rarely if ever been performed in any anatomical textbook.[76]

Leonardo missed some crucial details about the mechanics of blood circulation, which were discovered by William Harvey a hundred years later, and without chemistry he could not explain the oxygen exchange between the blood and the tissues of the lungs and body. But amazingly, he recognized many subtle features of cellular metabolism without even knowing about cells—for example, that heat energy supports the metabolic processes, that oxygen (the "vital spirits") sustains them, that there is a constant flow of oxygen from the heart to the body's periphery, and that the blood returns with waste products from the tissue metabolism. In other words, Leonardo developed a theory of the functioning of the heart and the flow of blood that allowed him to understand some of the essential features of biological life.

During the last decade of his life, while he was engaged in his most advanced studies of the human heart, Leonardo also became intensely interested in another aspect of the mystery of life—its origin in the processes of reproduction and embryonic development. That he had always considered embryology as an integral part of his studies of the human body is evident from the grandiose outline of a planned (but never assembled) treatise on the movements of the body, written about twenty years earlier. This long and detailed outline begins with the following sweeping declaration:

> This work should begin with the conception of man, and should describe the nature of the womb, and how the child lives in it, and to what stage it resides in it, and in what way it acquires life and food, and its growth, and what interval there is between one degree of growth and another, and what it is that pushes it out of the body of the mother.[77]

Leonardo's embryological studies, based largely on dissections of cows and sheep, included most of the topics he had listed and led him to remarkable observations and conclusions. While most authorities in his day believed that all inherited characteristics derived from the father, he asserted unequivocally: "The seed of the mother has equal power in the embryo to the seed of the father."[78]

He described the life processes of the fetus in the womb, including its nourishment through the umbilical cord, in astonishing detail, and he also made a series of measurements on animal fetuses to determine their rates of growth. Leonardo's embryological drawings are graceful and touching revelations of the mysteries surrounding the origins of human life (see Fig. E-1 on p. 261). In the words of physician Sherwin Nuland,

> [His] depiction of a five-month fetus in the womb is a thing of beauty. . . . It stands as a masterwork of art, and, considering the very little that was at the time understood of embryology, a masterwork of scientific perception as well.[79]

Leonardo knew very well that, ultimately, the nature and origin of life would remain a mystery, no matter how brilliant his scientific mind was. "Nature is full of infinite causes that have never occurred in experience,"[80] he declared in his late forties, and as he got older his sense of mystery deepened. Nearly all the figures in his last paintings have that smile that expresses the ineffable, often combined with a pointing finger. "Mystery to Leonardo," wrote Kenneth Clark, "was a shadow, a smile and a finger pointing into darkness."[81]