# THE SCIENCE OF LEONARDO

## INSIDE THE MIND OF THE GREAT GENIUS OF THE RENAISSANCE

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Author of *THE TAO OF PHYSICS*

# *Inside the Mind of the Great Genius of the Renaissance*

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# PREFACE

Leonardo da Vinci, perhaps the greatest master painter and genius of the Renaissance, has been the subject of hundreds of scholarly and popular books. His enormous oeuvre, said to include over 100,000 drawings and over 6,000 pages of notes, and the extreme diversity of his interests have attracted countless scholars from a wide range of academic and artistic disciplines.

However, there are surprisingly few books about Leonardo's science, even though he left voluminous notebooks full of detailed descriptions of his experiments, magnificent drawings, and long analyses of his findings. Moreover, most authors who have discussed Leonardo's scientific work have looked at it through Newtonian lenses, and I believe this has often prevented them from understanding its essential nature.

Leonardo intended to eventually present the results of his scientific research as a coherent, integrated body of knowledge. He never managed to do so, because throughout his life he always felt more compelled to expand, refine, and document his investigations than to organize them in a systematic way. Hence, in the centuries since his death, scholars studying his celebrated Notebooks have tended to see them as disorganized and chaotic. In Leonardo's mind, however, his science was not disorganized at all. It gave him a coherent, unifying picture of natural phenomena—but a picture that is radically different from that of Galileo, Descartes, and Newton.

Only now, five centuries later, as the limits of Newtonian science are becoming all too apparent and the mechanistic Cartesian world-

view is giving way to a holistic and ecological view not unlike Leonardo's, can we begin to appreciate the full power of his science and its great relevance for our modern era.

My intent is to present a coherent account of the scientific method and achievements of the great genius of the Renaissance and evaluate them from the perspective of today's scientific thought. Studying Leonardo from this perspective will not only allow us to recognize his science as a solid body of knowledge. It will also show why it cannot be understood without his art, nor his art without the science.

As a scientist and author, I depart in this book from my usual work. At the same time, however, it has been a deeply satisfying book to write, as I have been fascinated by Leonardo da Vinci's scientific work for over three decades. When I began my career as a writer in the early 1970s, my plan was to write a popular book about particle physics. I completed the first three chapters of the manuscript, then abandoned the project to write *The Tao of Physics*, into which I incorporated most of the material from the early manuscript. My original manuscript began with a brief history of modern Western science, and opened with the beautiful statement by Leonardo da Vinci on the empirical basis of science that now serves as the epigraph for this book.

Since paying tribute to Leonardo as the first modern scientist (long before Galileo, Bacon, and Newton) in my early manuscript, I have retained my fascination with his scientific work, and over the years have referred to it several times in my writings, without, however, studying his extensive Notebooks in any detail. The impetus to do so came in the mid-1990s, when I saw a large exhibition of Leonardo's drawings at The Queen's Gallery at Buckingham Palace in London. As I gazed at those magnificent drawings juxtaposing, often on the same page, architecture and human anatomy, turbulent water and turbulent air, water vortices, the flow of human hair and the growth patterns of grasses, I realized that Leonardo's systematic studies of living and nonliving forms amounted to a science of quality and wholeness that was fundamentally different from the mechanistic science of Galileo and Newton. At the core of his investigations, it seemed to me, was a persistent exploration of patterns, interconnecting phenomena from a vast range of fields.

Having explored the modern counterparts to Leonardo's approach,

known today as complexity theory and systems theory, in several of my previous books, I felt that it was time for me to study Leonardo's Notebooks in earnest and evaluate his scientific thought from the perspective of the most recent advances in modern science.

Although Leonardo left us, in the words of the eminent Renaissance scholar Kenneth Clark, "one of the most voluminous and complete records of a mind at work that has come down to us," his Notebooks give us hardly any clues to the author's character and personality.[1] Leonardo, in his paintings as well as in his life, seemed to cultivate a certain sense of mystery. Because of this aura of mystery and because of his extraordinary talents, Leonardo da Vinci became a legendary figure even during his lifetime, and his legend has been amplified in different variations in the centuries after his death.

Throughout history, he personified the age of the Renaissance, yet each era "reinvented" Leonardo according to the zeitgeist of the time. To quote Kenneth Clark again, "Leonardo is the Hamlet of art history whom each of us must recreate for himself."[2] It is therefore inevitable that in the following pages I have also had to reinvent Leonardo. The image that emerges from my account is, in contemporary scientific terms, one of Leonardo as a systemic thinker, ecologist, and complexity theorist; a scientist and artist with a deep reverence for all life, and as a man with a strong desire to work for the benefit of humanity.

The powerful intuition I had in that London exhibit, that the Leonardo I describe above is indeed "the Leonardo of our time," was confirmed by my subsequent research and exploration of the Notebooks. As art historian Martin Kemp wrote in the catalog of an earlier exhibit of Leonardo's drawings in the Hayward Gallery in London:

> It seems to me that there is a core to [Leonardo's] achievement, however imperfectly transmitted and received by different generations, that remains intuitively accessible. What has been sensed is that his artistic productions are more than art—that they are part of a vision embracing a profound sense of the interrelatedness of things. The full complexity of life in the context of the world is somehow implied when he characterises any of its constituent parts. . . . I believe that his vision of the totality of the world as

> a kind of single organism does speak to us with particular relevance today, now that our technological potential has become so awesome.[3]

Kemp's portrait of the Leonardo of that exhibit, characterized so eloquently in the passage above, mirrors my own. It is this Leonardo who will emerge from my exploration of his unique synthesis of science and art.

*Fritjof Capra*
*Berkeley, December 2006*

*Figure P-1: Leonardo's Self-Portrait, c. 1512, Biblioteca Reale, Turin*

# INTRODUCTION

## *An Interpreter of Nature*

In Western intellectual history, the Renaissance—a period stretching from the beginning of the fifteenth to the end of the sixteenth century—marks the period of transition from the Middle Ages to the modern world. In the 1460s, when the young Leonardo da Vinci received his training as painter, sculptor, and engineer in Florence, the worldview of his contemporaries was still entangled in medieval thinking. Science in the modern sense, as a systematic empirical method for gaining knowledge about the natural world, did not exist. Knowledge about natural phenomena, some accurate and some inaccurate, had been handed down by Aristotle and other philosophers of antiquity, and was fused with Christian doctrine by the Scholastic theologians who

presented it as the officially authorized creed. The authorities condemned scientific experiments as subversive, seeing any attack on Aristotle's science as an attack on the Church.

Leonardo da Vinci broke with this tradition. One hundred years before Galileo and Bacon, he single-handedly developed a new empirical approach to science, involving the systematic observation of nature, logical reasoning, and some mathematical formulations—the main characteristics of what is known today as the scientific method. He fully realized that he was breaking new ground. He humbly called himself *omo sanza lettere* ("an unlettered man"), but with some irony and with pride in his new method, seeing himself as an "interpreter between nature and humans." Wherever he turned there were new discoveries to be made, and his scientific creativity, combining passionate intellectual curiosity with great patience and experimental ingenuity, was the main driving force throughout his life.

For forty years, Leonardo collected his thoughts and observations in his celebrated Notebooks, together with descriptions of hundreds of experiments, drafts of letters, architectural and technological designs, and reminders to himself about future research and writing. Almost every page in these Notebooks is crowded with text and magnificent drawings. It is believed that the entire collection ran to 13,000 pages when Leonardo died without having sorted them, as he had intended. Over the subsequent centuries almost half of the original collection was lost, but over 6,000 pages have been preserved and translated from the original Italian. These manuscripts are now widely dispersed among libraries, museums, and private collections, some in large compilations known as codices, others as torn pages and isolated folios, and a few still as notebooks in their original bound forms.[1]

## *THE SCIENCE OF PAINTING*

Leonardo was gifted with exceptional powers of observation and visual memory. He was able to draw the complex swirls of turbulent water or the swift movements of a bird with a precision that would not be reached again until the invention of serial photography. He was well

aware of the extraordinary talent he possessed. In fact, he considered the eye as his principal instrument as both a painter and a scientist. "The eye, which is said to be the window of the soul," he wrote, "is the principal means whereby sensory awareness can most abundantly and magnificently contemplate the infinite works of nature."[2]

Leonardo's approach to scientific knowledge was visual. It was the approach of a painter. "Painting," he declares, "embraces within itself all the forms of nature."[3] This statement, in fact, is the key to understanding Leonardo's science. He asserts repeatedly, especially in his early manuscripts, that painting involves the study of natural forms, and he emphasizes the intimate connection between the artistic representation of those forms and the intellectual understanding of their intrinsic nature and underlying principles. For example, in the collection of his notes on painting, known as *Trattato della pittura (Treatise on Painting)*, he writes:

> The science of painting extends to all the colors of the surfaces of bodies, and to the shapes of the bodies enclosed by those surfaces. . . . [Painting] with philosophic and subtle speculation considers all the qualities of forms. . . . Truly this is science, the legitimate daughter of nature, because painting is born of nature.[4]

For Leonardo, painting is both an art and a science—a science of natural forms, of qualities, quite different from the mechanistic science that would emerge two hundred years later. Leonardo's forms are living forms, continually shaped and transformed by underlying processes. Throughout his life he studied, drew, and painted the rocks and sediments of the earth, shaped by water; the growth of plants, shaped by their metabolism; and the anatomy of the animal (and human) body in motion.

## THE NATURE OF LIFE

Nature as a whole was alive for Leonardo. He saw the patterns and processes in the microcosm as being similar to those in the macrocosm.

He frequently drew analogies between human anatomy and the structure of the Earth, as in the following beautiful passage from the Codex Leicester:

> We may say that the Earth has a vital force of growth, and that its flesh is the soil; its bones are the successive strata of the rocks which form the mountains; its cartilage is the porous rock, its blood the veins of the waters. The lake of blood that lies around the heart is the ocean. Its breathing is the increase and decrease of the blood in the pulses, just as in the Earth it is the ebb and flow of the sea.[5]

While the analogy between microcosm and macrocosm goes back to Plato and was well known throughout the Middle Ages and the Renaissance, Leonardo disentangled it from its original mythical context and treated it strictly as a scientific theory. Today we know that some of the analogies in the passage quoted above are flawed, and in fact Leonardo himself corrected some of them late in his life.[6] However, we can easily recognize Leonardo's statement as a forerunner of today's Gaia theory—a scientific theory that views the earth as a living, self-organizing, and self-regulating system.[7]

At the most fundamental level, Leonardo always sought to understand the nature of life. This has often escaped earlier writers, because until recently the nature of life was defined by biologists only in terms of cells and molecules, to which Leonardo, living two centuries before the invention of the microscope, had no access. But today, a new systemic understanding of life is emerging at the forefront of science—an understanding in terms of metabolic processes and their patterns of organization. And those are precisely the phenomena Leonardo explored throughout his life.

## *A SYSTEMIC THINKER*

Leonardo da Vinci was what we would call, in today's scientific parlance, a systemic thinker.[8] Understanding a phenomenon, for him, meant connecting it with other phenomena through a similarity of

patterns. When he studied the proportions of the human body, he compared them to the proportions of buildings in Renaissance architecture. His investigations of muscles and bones led him to study and draw gears and levers, thus interlinking animal physiology and engineering. Patterns of turbulence in water led him to observe similar patterns in the flow of air; and from there he went on to explore the nature of sound, the theory of music, and the design of musical instruments.

This exceptional ability to interconnect observations and ideas from different disciplines lies at the very heart of Leonardo's approach to learning and research. At the same time, it was also the reason why he often got carried away and extended his investigations far beyond their original role in the formulation of a "science of painting," exploring almost the entire range of natural phenomena known at his time as well as many others previously unrecognized.

Leonardo's scientific work was virtually unknown during his lifetime and remained hidden for over two centuries after his death in 1519. His pioneering discoveries and ideas had no direct influence on the scientists who came after him, although during the subsequent 450 years his conception of a science of living forms would emerge again at various times. During those periods, the problems he had struggled with were revisited with increasing levels of sophistication, as scientists advanced in their understanding of the structure of matter, the laws of chemistry and electromagnetism, cellular and molecular biology, genetics, and the critical role of evolution in shaping the forms of the living world.

Today, from the vantage point of twenty-first-century science, we can recognize Leonardo da Vinci as an early precursor of an entire lineage of scientists and philosophers whose central focus was the nature of organic form. They include Immanuel Kant, Alexander von Humboldt, and Johann Wolfgang von Goethe in the eighteenth century; Georges Cuvier, Charles Darwin, and D'Arcy Thompson in the nineteenth; Alexander Bogdanov, Ludwig von Bertalanffy, and Vladimir Vernadsky in the early twentieth; and Gregory Bateson, Ilya Prigogine, and Humberto Maturana in the late twentieth century; as well as contemporary morphologists and complexity theorists like Brian Goodwin, Ian Stewart, and Ricard Solé.

Leonardo's organic conception of life has continued as an undercur-

rent of biology throughout the centuries, and during brief periods came to the fore and dominated scientific thought. However, none of the scientists in that lineage were aware that the great genius of the Renaissance had already pioneered many of the ideas they were exploring. While Leonardo's manuscripts were gathering dust in ancient European libraries, Galileo Galilei was being celebrated as the "father of modern science." I cannot help but argue that the true founder of modern science was Leonardo da Vinci, and I wonder how Western scientific thought would have developed had his Notebooks been known and widely studied soon after his death.

## *SYNTHESIS OF ART AND SCIENCE*

To describe nature's organic forms mathematically, we cannot use Euclidean geometry, nor the classical equations of Newtonian physics. We need a new kind of qualitative mathematics. Today, such a new mathematics is being formulated within the framework of complexity theory, technically known as nonlinear dynamics.[9] It involves complex nonlinear equations and computer modeling, in which curved shapes are analyzed and classified with the help of topology, a geometry of forms in movement. None of this was available to Leonardo, of course. But amazingly, he experimented with a rudimentary form of topology in his mathematical studies of "continuous quantities" and "transmutations," long before this important branch of modern mathematics was developed by Henri Poincaré in the early twentieth century.[10]

Leonardo's principal tool for the representation and analysis of nature's forms was his extraordinary facility of drawing, which almost matched the quickness of his vision. Observation and documentation were fused into a single act. He used his artistic talent to produce drawings that are stunningly beautiful and at the same time serve as geometric diagrams. For Leonardo, drawing was the perfect vehicle to formulate his conceptual models—a perfect "mathematics" for his science of organic forms.[11]

The dual role of Leonardo's drawings—as art and as tools of scientific analysis—shows us why his science cannot be understood without his art, nor his art without his science. His assertion that "painting em-

braces in itself all the forms of nature" cuts both ways. In order to practice his art, he needed the scientific understanding of the forms of nature; in order to analyze the forms of nature, he needed the artistic ability to draw them.

In addition to his keen intellect and powers of observation, his experimental ingenuity, and his great artistic talents, Leonardo also had a very practical bent. As he pursued his investigations of nature's forms, beholding them with the eye of a scientist and painter, the useful applications of his discoveries were never far from his mind. He spent a major part of his life conceiving machines of all kinds, inventing numerous mechanical and optical devices, and designing buildings, gardens, and cities.

When he studied water, he saw it not only as the medium of life and the driving force of nature, but also as a source of power for industrial systems, similar to the role that steam—another form of water—would play in the Industrial Revolution three centuries later. His extensive investigations of the flows of air and wind and the flight of birds led him to invent various flying machines, many of them based on sound aerodynamic principles. Indeed, Leonardo's achievements as a designer and engineer are on a par with his accomplishments as an artist and scientist.

## *THE EYE AND THE APPEARANCE OF FORMS*

In his *Treatise on Painting*, Leonardo makes clear that painting is the unifying perspective and integrating thread that runs through all his fields of study. From this work, a coherent conceptual structure emerges, which he might have intended to use for the eventual publications of his Notebooks.

Like all true scientists, Leonardo based his science on systematic observation. Hence his starting point is the human eye. His careful investigations of the anatomy of the eye and the origin of vision were unparalleled in his time. He paid particular attention to the connections between the eye and the brain, which he demonstrated in a series of beautiful drawings of the human skull. Using brilliant anatomical dissections, Leonardo displayed for the first time the complete path of vi-

sion through the pupil and lens to the optic nerve, and all the way to a specific cavity in the brain, known to neurologists today as the third cerebral ventricle.[12]

This is where he located the "seat of the soul," where all sense impressions meet. Leonardo's concept of the soul comes very close to what cognitive scientists today call "cognition," the process of knowing.[13] His theory of how sensory impulses travel along the nerves from the sense organs to the brain is so ingenious that I doubt if neuroscientists today could conceive of anything better, were they given the restrictions of having to work without any knowledge of electromagnetism, biochemistry, and microbiology.

Leonardo saw his discoveries in optics and the physiology of vision as the grounding of his science of painting, beginning with the science of perspective, the outstanding innovation of Renaissance art. "Painting is based on perspective," he explains, "and perspective is nothing else than a thorough knowledge of the function of the eye."[14] From perspective, he moved on to explore the geometry of light rays (known today as geometrical optics), the effects of light falling on spheres and cylinders, the nature of shadow and of contrasts, and the juxtaposition of colors.

These systematic studies, illustrated in long series of intricate drawings, were the scientific basis of Leonardo's extraordinary artistic ability to understand and render the most subtle visual complexities. Most renowned was his invention and mastery of a special art of shading—a melting of shades, known as sfumato—which delicately blurs the outlines of bodies. In the words of art historian Daniel Arasse,

> The supreme expression of the science of painting and of its divine character, Leonardo's *sfumato* was the power behind the poetry of his paintings and the mystery that seems to emanate from them.[15]

Eventually, these sophisticated studies of the effects of light and shade led Leonardo to thoroughly investigate the very nature of light. With only the most rudimentary instruments, he used his phenomenal powers of observation, his ability to recognize similarities of patterns, and the great intuitive understanding of light he had acquired as a painter

to formulate concepts that were diametrically opposed to the ideas of his contemporaries, but were almost identical to those Christian Huygens would propose two hundred years later in his famous wave theory of light.[16]

## *THE LIVING FORMS OF NATURE*

Leonardo's studies of living forms began with their appearance to his painter's eye, and then proceeded to detailed investigations of their intrinsic nature. 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 the flight of birds.

The science of living forms, for Leonardo, is a science of movement and transformation, whether he studies mountains, rivers, plants, or the human body. To understand the human form means to understand the body in motion. Leonardo demonstrated in countless elaborate and beautiful drawings how nerves, muscles, tendons, bones, and joints work together to move the limbs; how limbs and facial expressions perform gestures and actions.

As always, Leonardo used the insights he gained from this extensive research in his paintings. In the words of Daniel Arasse,

> From the early *Madonnas*, through the portraits, to *St. John the Baptist*, Leonardo caught the figure in motion. The immediate and exceptional impact of *The Last Supper* was largely due to the fact that Leonardo replaced the traditional arrangement with a rhythmical composition that considerably changed the very idea of the subject.[17]

As a painter, Leonardo felt that he should use gestures to portray the frames of mind and emotions that provoked them. He asserted that, in the painting of a human figure, the most important task was to "ex-

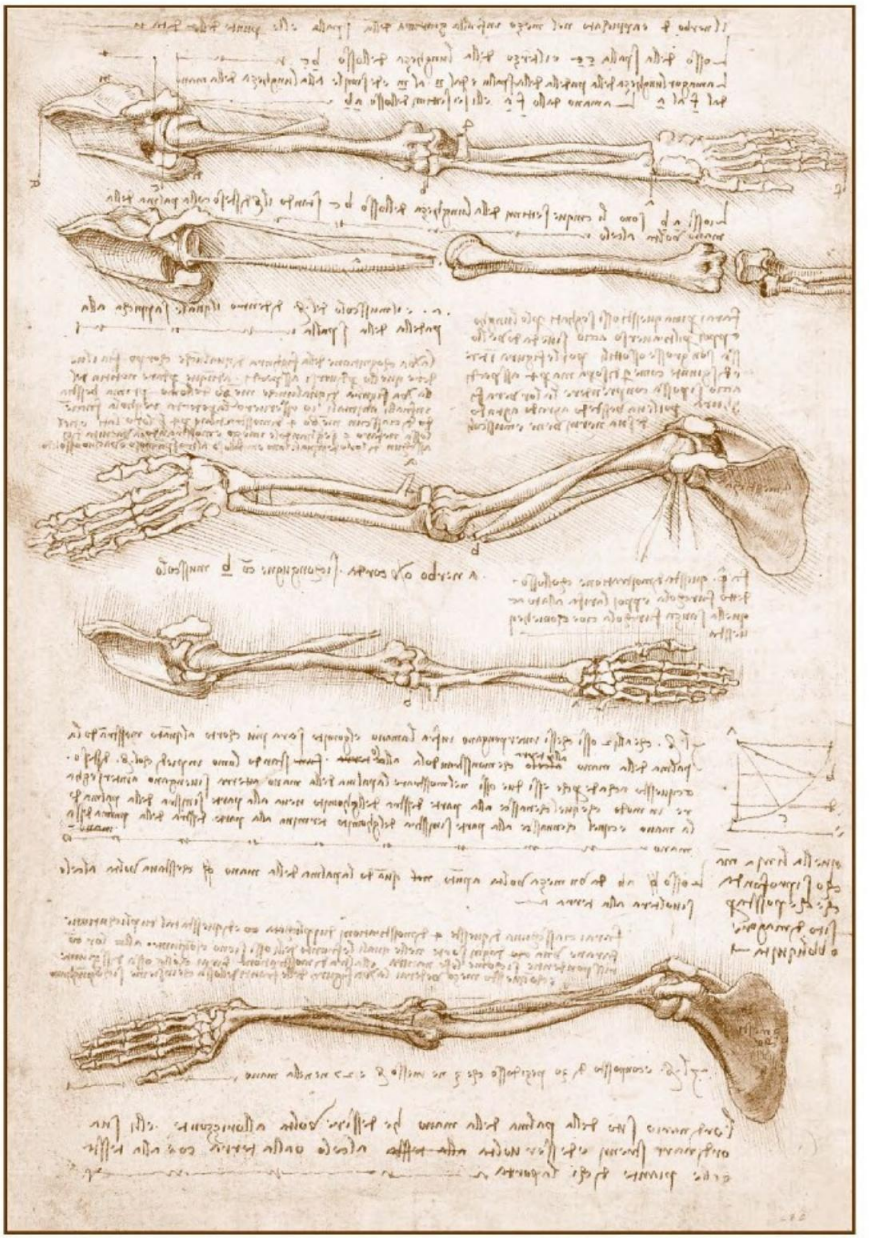

*Figure I-1: The Mechanisms of the Arm, c. 1510, Anatomical Studies, folio 135v*

press in gesture the passion of its soul."[18] Indeed, to portray the body's expression of the human spirit was the artist's highest aspiration, in Leonardo's view. And it was one in which he himself excelled, as the paintings of his mature period attest. As art historian Irma Richter explains in the introductory comments to her classic selections from the Notebooks, for Leonardo, "the human body was an outward and visible expression of the soul; it was shaped by its spirit."[19] We shall see that this view of soul and spirit, unmarred by the mind-body split that René Descartes would introduce in the seventeenth century, is perfectly consistent with the conception of the "embodied mind" in today's cognitive science.[20]

Unlike Descartes, Leonardo never thought of the body as a machine, even though he was a brilliant engineer who designed countless machines and mechanical devices. He clearly recognized, and documented in superb renderings, that the anatomies of animals and humans involve mechanical functions (see Fig. I-1). "Nature cannot give movement to animals without mechanical instruments," he explained.[21] But that did not imply for him that living organisms were machines. It only implied that, in order to understand the movements of the animal body, he needed to explore the principles of mechanics, which he did for many years in a thorough and systematic way. He clearly understood that the means of the body's movements were mechanical. But for Leonardo, their origin lay in the soul, the nature of which was not mechanical but spiritual.[22]

## *LEONARDO'S LEGACY*

Leonardo did not pursue science and engineering to dominate nature, as Francis Bacon would advocate a century later. He had a deep respect for life, a special compassion for animals, and great awe and reverence for nature's complexity and abundance. While a brilliant inventor and designer himself, he always thought that nature's ingenuity was vastly superior to human design. He felt that we would be wise to respect nature and learn from her. It is an attitude that has reemerged today in the practice of ecological design.[23]

Leonardo's synthesis of art and science is infused with a deep aware-

ness of ecology and systems thinking. It is not surprising that he spoke with great disdain of the so-called "abbreviators," the reductionists of his time:

> The abbreviators of works do injury to knowledge and to love. . . . Of what value is he who, in order to abbreviate the parts of those things of which he professes to give complete knowledge, leaves out the greater part of the things of which the whole is composed? . . . Oh human stupidity! . . . You don't see that you are falling into the same error as one who strips a tree of its adornment of branches full of leaves, intermingled with fragrant flowers or fruit, in order to demonstrate that the tree is good for making planks.[24]

This statement is revealing testimony of Leonardo's way of thinking and is also ominously prophetic. Reducing the beauty of life to mechanical parts and valuing trees only for their lumber is an eerily accurate characterization of the mind-set that dominates our world today. In my view, this makes Leonardo's legacy all the more relevant to our time.

Our sciences and technologies have become increasingly narrow in their focus, and we are unable to understand our multifaceted problems from an interdisciplinary perspective. We urgently need a science that honors and respects the unity of all life, that recognizes the fundamental interdependence of all natural phenomena, and reconnects us with the living earth. What we need today is exactly the kind of thinking and science Leonardo da Vinci anticipated and outlined five hundred years ago, at the height of the Renaissance and the dawn of the modern scientific age.

PART ONE

# LEONARDO, THE MAN

# ONE

## *Infinite Grace*

The earliest literary portrait of Leonardo da Vinci, and to me still the most moving, is that by the Tuscan painter and architect Giorgio Vasari in his classic book *Lives of the Artists*, published in 1550.[1] Vasari was only eight years old when Leonardo died, but he gathered information about the master from many artists who had known him and remembered him well, most notably Leonardo's close friend and disciple Francesco Melzi. An acquaintance of Leonardo, the surgeon and art collector Paolo Giovio, wrote a short eulogy, but it is unfinished and merely a page long.[2] Vasari's chapter, "Life of Leonardo da Vinci," therefore, is as close as we can come to a contemporary account.

Besides being an accomplished painter and architect,

Vasari was a keen collector of drawings by famous masters and of stories about them. The idea of writing a book on the history of Italian art from the thirteenth to the sixteenth centuries was suggested to him by Giovio during a dinner party in Rome.[3] The book became a bestseller when it was first published, and its wide popular appeal has endured over the centuries due to the author's lively and colorful portraits, replete with charming anecdotes. Through a series of engaging stories about the lives of its greatest artists, Vasari's *Lives* conveyed the revolutionary nature of the Italian Renaissance. In spite of many inaccuracies and a tendency toward referring to legends and idolizing, Vasari's work remains the principal source for anyone interested in that period of European art and culture.

## *QUALITIES AND APPEARANCE*

The opening paragraphs of Vasari's chapter on Leonardo are an emphatic declaration of the master's exceptional qualities and appearance:

> In the normal course of events many men and women are born with various remarkable qualities and talents; but occasionally, in a way that transcends nature, a single person is marvelously endowed by heaven with beauty, grace, and talent in such abundance that he leaves other men far behind, all his actions seem inspired, and indeed everything he does clearly comes from God rather than from human art.
>
> Everyone acknowledged that this was true of Leonardo da Vinci, an artist of outstanding physical beauty who displayed infinite grace in everything he did and who cultivated his genius so brilliantly that all problems he studied he solved with ease. He possessed great strength and dexterity; he was a man of regal spirit and tremendous breadth of mind; and his name became so famous that not only was he esteemed during his lifetime but his reputation endured and became even greater after his death.

Vasari's effusive portrait of Leonardo may seem exaggerated, but his description is echoed in many contemporary accounts and references, in

*Figure 1-1: Andrea del Verrocchio,* David, *Museo Nazionale, Florence*

which Leonardo was often compared to the classical geniuses and sages of antiquity—Archimedes, Pythagoras, and most frequently Plato.[4] Indeed, when Raphael, another great master of the Italian Renaissance, painted his fresco *The School of Athens* in the Vatican, he gave Plato the features of Leonardo, dressing him in a rose-colored toga (a color favored by Leonardo), with his index finger raised in a characteristic gesture well known from Leonardo's paintings.

Leonardo's physical beauty in his youth and middle-aged years must have been exceptional, as it is mentioned by all his contemporary commentators, even though this was not customary at the time. An anonymous writer called the Anonimo Gaddiano exclaimed, "He was so unusual and many-sided that nature seemed to have produced a miracle in him, not only in the beauty of his person, but in the many gifts with which she endowed him and which he fully mastered."[5] Others marveled at the unique combination of physical strength and grace he seemed to embody. Many authors, including Vasari, referred to him with the ultimate epithet—*il divino*.

As a youth, Leonardo liked to dress flamboyantly. "He wore a rose-colored cloak," the Anonimo Gaddiano tells us, "which came only to his knees, although at the time long vestments were the custom. His beard came to the middle of his breast and was well-combed and curled."

As he grew older, Leonardo apparently dressed more conventionally, but his appearance was always elegant and refined. Paolo Giovio described him as "the arbiter of all questions relating to beauty and elegance, especially pageantry." Leonardo's own description of the painter's inherent refinement is revealing as well:

> The painter sits in front of his work at great ease, well-dressed, and wielding a very light brush with delicate colors. He adorns himself with the clothes he fancies; his home is clean and filled with delightful pictures, and he is often accompanied by music or readers of various beautiful works.[6]

There exists no confirmed portrait of Leonardo as a young man, but legend has it that he was the model for several angels and other youthful figures portrayed by Renaissance artists. The most credible of them

is the lovely adolescent *David* sculpted by Andrea del Verrocchio during the time Leonardo was his student (see Fig. 1-1). The slender figure, wavy hair, and strikingly handsome face certainly match the contemporary descriptions of the young Leonardo, and art historians have pointed out that several of the statue's facial characteristics seem to foreshadow those in the well-known portraits of the old master.[7]

There are quite a few portraits of Leonardo as an older man, most of them idealizing him as a venerable sage.[8] The most authentic is that which is considered the artist's only existing self-portrait, a captivating, highly detailed drawing in red chalk that he made when he was about sixty, although he appears older than his age (see Fig. P-1 on p. xxii). The drawing is housed in the Biblioteca Reale in Turin and is known as the Turin self-portrait. Unfortunately, it has been severely affected by centuries of exposure to air and light. The paper is now covered with "fox marks" (rusty-brown spots caused by excessive moisture and subsequent accumulation of iron salts), and the drawing is rarely exhibited in public.

In spite of its poor condition, the Turin self-portrait, which has been reproduced in countless posters and books, exerts a powerful effect on the viewer. This is even more true if one is fortunate enough to spend some time with the original, viewing it from different angles and distances, revealing the portrait's complex and subtle expressions. Leonardo drew this portrait at a time of personal uncertainty and discontent. He was well aware that the greater part of his life was behind him; his eyes had weakened and his health was failing. He was living in Rome at the time, where he was revered. But already he was beginning to become out of fashion as an artist, eclipsed by younger rivals like Raphael and Michelangelo, who were in their prime and were the favorites of the papal court.

In Leonardo's self-portrait, this unhappy time is reflected in a line of disillusionment, or perhaps contempt, around the mouth. Yet, under the bushy brows and majestic forehead, his eyes—the "windows of the soul"—have preserved the quiet intensity of his gaze as well as a deep serenity. The resulting expression, to me, is that of a powerful, critical intellect, tempered by wisdom and compassion.

Over the years, the Turin self-portrait has become not only the iconic image of Leonardo, but the model for the archetypal portrait of

the old sage in the centuries after him. "This great furrowed mountain of a face," wrote art historian Kenneth Clark, "with its noble brow, cavernous eyes, and undulating foothills of beard is like the faces of all the great men of the nineteenth century as the camera has preserved them for us—Darwin, Tolstoy, Walt Whitman."[9]

A quality that is not visible in Leonardo's self-portrait but was always mentioned by his contemporaries was his kind and gentle nature, in the words of the duchess Isabella d'Este, "this air of sweetness and gentleness that is so characteristic of him." "Leonardo's disposition was so lovable that he commanded everyone's affection," Vasari writes. "He was so generous that he sheltered and fed all his friends, rich or poor." He was also eloquent and charming in conversation. In fact, Vasari claimed he was so persuasive that he could "bend other people to his own will."

Leonardo combined this gentle and charming disposition with great physical strength. In his younger years he was apparently quite an athlete, "most skillful in lifting weights," as the Anonimo Gaddiano tells us, and an excellent horseman. According to Vasari, "he was physically so strong that he could withstand any violence; with his right hand he would bend the iron ring of a doorbell or a horseshoe as if they were lead." Vasari may have exaggerated Leonardo's strength (and we know that Leonardo was left-handed), but his athletic prowess seems to have been well known.

During his years in Milan, he entertained the court with fables, songs, and charming conversation. "He sang beautifully to his own accompaniment on the *lira* to the delight of the entire court," we are told by Paolo Giovio. But Leonardo also pursued his scientific research with intense concentration and needed to escape frequently to spend long periods of time alone. "The painter or draftsman must be solitary," he wrote in the *Treatise on Painting*, "and most of all when he is intent on those speculations and considerations which, continually appearing before the eyes, give material to the memory to be well stored."[10] These frequent withdrawals into periods of solitude, spent in contemplation and sustained observations of nature, likely contributed to the air of mystery that surrounded him.

## *CHARACTER TRAITS*

Throughout his life, Leonardo displayed an air of serene self-confidence, which helped him overcome professional setbacks and disappointments with equanimity and allowed him to calmly pursue his research even during times of great political turbulence. He was well aware of his unique genius and skill, yet he never boasted about them. Nowhere in his Notebooks does he vaunt the originality of his inventions or discoveries, nor does he flaunt the superiority of his ideas, even as he explains how they differ from traditional beliefs. This lack of arrogance and ego was remarkable indeed.

Another quality that distinguished him was his passion for life and for all living things. He immersed himself in the study of living forms not only intellectually, but emotionally as well. He held a great awe and reverence for nature's creativity, and felt particular compassion for animals. His love of horses was well known to his contemporaries, and can be seen in his drawings, in which he used his acute powers of observation to render the animals' movements and "noble proportions" in exquisite detail. Vasari claimed that Leonardo always kept horses. Equally touching is Vasari's famous story of Leonardo buying birds in the marketplace, so that he might set them free:

> Often when he was walking past the places where birds were sold he would pay the price asked, take them from their cages, and let them fly off into the air, giving them back their lost freedom.

His love of animals was also the reason Leonardo became a vegetarian—something unheard-of in Italy during the Renaissance, and therefore widely noticed. Leonardo's justification for his vegetarianism combines his firm moral stance with keen scientific observation. He argued that, unlike plants, animals are sensitive to pain because they are capable of movement, and he did not want to cause them pain and suffering by killing them for food:

> Nature has ordained that living organisms with the power of movement should experience pain in order to preserve those parts which might diminish or be destroyed by movement. Living organisms without the power of movement do not have to strike against any opposing objects, so that pain is not necessary in plants, and hence when they are broken they do not feel pain as do animals.[11]

In other words, in Leonardo's mind, animals develop sensitivity to pain because it gives them a selective advantage in avoiding injury when they move about.

By all accounts, Leonardo was a man of unusual tenderness. He had tremendous compassion for the suffering of people and animals. He was vehemently opposed to war, which he called *pazzia bestialissima* ("most bestial madness"). In view of this, it seems contradictory that he should have offered his services as military engineer to various rulers of his time.

Part of the answer to this contradiction had to do with his pragmatic attitude when it came to securing a stable income that would allow him to pursue his scientific research. With his extraordinary talent for designing machines of all kinds, and in view of the endless political rivalries and conflicts on the Italian peninsula, Leonardo shrewdly recognized that employment as a consulting military engineer and architect was one of the best ways to secure his financial independence.

However, it is also clear from his Notebooks that he was fascinated by the destructive engines of war, perhaps in the same way that natural cataclysms and disasters fascinated him. He spent considerable time designing and drawing machines of destruction—bombards, explosive cannonballs, catapults, giant crossbows, and the like, even as he remained adamantly opposed to war and violence.

As biographer Serge Bramly points out, despite his many years of service as military engineer, Leonardo never participated in any offensive action. Most of his advice consisted of designing structures to defend and preserve a town or city.[12] During a conflict between Florence and Pisa, he proposed to divert the river Arno as a means to avoid a bloody battle. He went on to add that this should be followed up with

the construction of a navigable waterway that would reconcile the combatants and bring prosperity to both cities.

Leonardo's most explicit condemnation of war consists of a long and detailed description of how to paint a battle, written when he was in his late thirties. Even a few excerpts from this text, which runs over several pages, reveal how vividly the artist intended to picture the horrors of war:

> You will first paint the smoke of the artillery, mingled in the air with the dust raised by the commotion of horses and combatants. . . . Let the air be full of arrows of all kinds, some shooting upwards, some falling, some flying level. The bullets from the firearms will leave a trail of smoke behind them. . . . If you show a man who has fallen to the ground, reproduce his skid marks in the dust, which has been turned into blood-stained mire. . . . Paint a horse dragging the dead body of its master, and leaving behind him in the dust and mud the track where the body was dragged along. Make the vanquished and beaten pale, with brows raised and knit, and the skin above their brows furrowed with pain. . . . Represent others crying out with their mouths wide open and running away . . . ; others in the agonies of death grinding their teeth, rolling their eyes, with their fists clenched against their bodies, and their legs contorted.[13]

A decade after he wrote this, Leonardo, who was then over fifty and at the height of his fame, received a commission for a huge mural, which gave him the opportunity to turn his words into action. The Signoria, the Florentine city government, had decided to celebrate the military glory of Florence by decorating its new council chamber with two large frescoes depicting its victories in two historic battles—against Milan at Anghiari and against Pisa at Cascina. The Signoria commissioned the former fresco from Leonardo and the latter from his young rival Michelangelo.

*The Battle of Anghiari* was the most important public commission Leonardo had ever received. He completed the huge cartoon (or sketch) within a year, as stipulated in his contract, and then spent over half a

*Figure 1-2: Peter Paul Rubens after Leonardo,* The Struggle for the Standard, *c. 1600–1608, Musée du Louvre, Paris*

year painting the fresco's central scene, a group of horsemen fighting for a standard. Because of technical problems that resulted in the rapid deterioration of the mural, he never completed the huge painting. (Michelangelo left Florence for Rome to paint the frescoes on the ceiling of the Sistine Chapel, without starting his *Battle of Cascina*.) The central part of Leonardo's composition, known as *The Struggle for the Standard*, remained on the wall of the council chamber in the Palazzo Vecchio for almost sixty years before the Signoria finally had its last traces removed. During those decades it dazzled spectators and was copied by several other Renaissance masters.

Leonardo left many preparatory drawings for *The Battle of Anghiari*, from which art historians have reconstructed the painting's general composition.[14] While he intended to present the unfolding of the battle with great clarity and historical accuracy, Leonardo used the central

Leonardo was as secretive about his sexuality as he was about other aspects of his personal life.

Leonardo was equally secretive about his scientific work. Although he intended to eventually publish the results of his investigations, he kept them hidden away during his entire life, apparently out of fear that his ideas might be stolen.[19] In Milan, he designed his studio so that the platform holding his work could be lowered through the floor to the story below, using a system of pulleys and counterweights, to hide it from inquisitive eyes whenever he was not working.[20]

Much has been made in this context of the fact that Leonardo, who was left-handed, wrote all his notes in mirror writing, from right to left. In fact, he could write with both hands and in either direction. But, like many left-handed people, he probably found it more convenient and faster to write from right to left when he jotted down his personal notes. On the other hand, as Bramly points out, this extraordinary handwriting also suited very well his taste for secrecy.[21]

The main reason Leonardo did not share his scientific knowledge with others, although he shared his knowledge of painting with fellow artists and disciples, was that he regarded it as his intellectual capital—the basis of his skills in engineering and stagecraft, which were the main sources of his regular income. He must have feared that sharing this body of knowledge would have diminished his chances of steady employment.

Moreover, Leonardo did not see science as a collective enterprise the way we see it now. In the words of art historian and classicist Charles Hope, "He had . . . no real understanding of the way in which the growth of knowledge was a cumulative and collaborative process, as was so evidently the case with the major intellectual enterprise of his time, the recovery of the heritage of classical antiquity."[22] Leonardo had no formal education and was not able to read the scholarly books of the time in Latin, but he studied Italian translations whenever he could obtain them. He sought out scholars in various fields to borrow books and elicit information, but he did not share his own discoveries with them—neither in conversations, as far as we know, nor in correspondence or publications.

This secrecy about his scientific work is the one significant respect in which Leonardo was not a scientist in the modern sense. If he had

shared his discoveries and discussed them with the intellectuals of his time, his influence on the subsequent development of Western science might well have been as profound as his impact on the history of art. As it was, he had little influence on the scientists who came after him, because his scientific work was hidden during his lifetime and remained locked in his Notebooks long after his death. As the eminent Leonardo scholar Kenneth Keele reflected, "The intellectual loneliness of the artist-scientist Leonardo was not merely contemporary; it has lasted for centuries."[23]

## *SIGNS OF GENIUS*

Since Leonardo da Vinci is widely viewed as the archetype of a genius, it is interesting to ask ourselves what we mean by that term. On what grounds are we justified in calling Leonardo a genius, and how does he compare with other artists and scientists known as geniuses?

During Leonardo's time, the term "genius" did not have our modern meaning of a person endowed with extraordinary intellectual and creative powers.[24] The Latin word *genius* originated in Roman religion, where it denoted the spirit of the *gens*, the family. It was understood as a guardian spirit, first associated with individuals and then also with peoples and places. The extraordinary achievements of artists or scientists were attributed to their genius, or attendant spirit. This meaning of genius was prevalent throughout the Middle Ages and the Renaissance. In the eighteenth century, the meaning of the word changed to its familiar modern meaning to denote these individuals themselves, as in the phrase "Newton was a genius."

Regardless of the term used, the fact that certain individuals possess exceptional and inexplicable creative powers beyond the reach of ordinary mortals was recognized throughout the ages. It was often associated with divine inspiration, especially in connection with poets. For example, in the twelfth century, the German abbess and mystic Hildegard von Bingen was famous throughout Europe as a naturalist, composer, visual artist, poet, and playwright. She herself, however, took no credit for the amazing range and depth of her talents but commented simply that she was "a feather on the breath of God."[25]

In the Italian Renaissance, the association of exceptional creative powers with divine inspiration was expressed in a very direct way by bestowing on those individuals the epithet *divino*. Among the Renaissance masters, Leonardo as well as his younger contemporaries Raphael and Michelangelo were acclaimed as divine.

Since the development of modern psychology, neuroscience, and genetic research, there has been a lively discussion about the origins, mental characteristics, and genetic makeup of geniuses. However, numerous studies of well-known historical figures have shown a bewildering diversity of hereditary, psychological, and cultural factors, defying all attempts to establish some common pattern.[26] While Mozart was a famous child prodigy, Einstein was a late bloomer. Newton attended a prestigious university, whereas Leonardo was essentially self-taught. Goethe's parents were well educated and of high social standing, but Shakespeare's seem to have been relatively undistinguished; and the list goes on.

In spite of this wide range of backgrounds, psychologists have been able to identify a set of mental attributes that seem to be distinctive signs of genius, in addition to exceptional talent in a particular field.[27] All these were characteristic of Leonardo to a very high degree.

The first is an intense curiosity and great enthusiasm for discovery and understanding. This was indeed an outstanding quality of Leonardo, whom Kenneth Clark called "the most relentlessly curious man in history."[28] Another striking sign of genius is an extraordinary capacity for intense concentration over long periods of time. Isaac Newton apparently was able to hold a mathematical problem in his mind for weeks until it surrendered to his mental powers. When asked how he made his remarkable discoveries, Newton is reported to have replied, "I keep the subject constantly before me and wait until the first dawnings open little by little into the full light."[29] Leonardo seems to have worked in a very similar way, and most of the time not only on one but on several problems simultaneously.

We have a vivid testimony of Leonardo's exceptional powers of concentration from his contemporary Matteo Bandello, who described how as a boy he watched the artist paint *The Last Supper*. He would see the master arrive early in the morning, Bandello tells us, climb up onto the scaffolding, and immediately start to work:

> He sometimes stayed there from dawn to sundown, never putting down his brush, forgetting to eat and drink, painting without pause. He would also sometimes remain two, three, or four days without touching his brush, although he spent several hours a day standing in front of the work, arms folded, examining and criticizing the figures to himself. I also saw him, driven by some sudden urge, at midday, when the sun was at its height, leaving the Corte Vecchia, where he was working on his marvelous clay horse, to come straight to Santa Maria delle Grazie, without seeking shade, and clamber up onto the scaffolding, pick up a brush, put in one or two strokes, and then go away again.[30]

Closely associated with the powers of intense concentration that are characteristic of geniuses seems to be their ability to memorize large amounts of information in the form of a coherent whole, a single gestalt. Newton kept mathematical proofs he had derived for months in his mind before eventually writing them down and publishing them. Goethe is said to have entertained his fellow passengers on long coach journeys by reciting his novels to them, word for word, before committing them to paper. And then there is the famous story of Mozart, who as a child wrote out a note-perfect score of Gregorio Allegri's *Miserere*, a complex chant for a five-part choir, after hearing it only once.

Leonardo would follow people with striking facial features for hours, memorize their appearance, and then draw them when he was back in his studio, reportedly with complete accuracy. The Milanese painter and writer Giovanni Paolo Lomazzo tells the story of how Leonardo once wished to paint some peasants laughing:

> He chose certain men whom he thought appropriate for his purpose, and, after getting acquainted with them, arranged a feast for them with some of his friends. Sitting close to them he then proceeded to tell the maddest and most ridiculous tales imaginable, making them, who were unaware of his intentions, laugh uproariously. Whereupon he observed all their gestures very attentively and those ridiculous things they were doing, and impressed them

> on his mind; and after they had left, he retired to his room and there made a perfect drawing which moved those who looked at it to laughter, as if they had been moved by Leonardo's stories at the feast.[31]

In subsequent chapters I shall recount the chronology of Leonardo's life, following its trajectory from Vinci, the little hamlet, to Florence, the thriving center of Renaissance art, to the Sforza court in Milan, to the papal court in Rome, and to his final home in the Loire valley in the palace of the king of France. However, the documentations of this rich and fascinating life contain hardly any clues to the sources of Leonardo's genius. Indeed, as classicist Penelope Murray observes in the introduction to her anthology *Genius: The History of an Idea*:

> There remains something fundamentally inexplicable about the nature of such prodigious powers. We attribute the extraordinary quality of, for example, Shakespeare's poetry, Mozart's music and Leonardo's paintings to the genius of their creators because we recognize that such works are not simply the product of learning, technique, or sheer hard work. Of course we can trace sources and influences . . . but no amount of analysis has yet been able to explain the capacities of those rare and gifted individuals who can produce creative work of lasting quality and value.[32]

In view of the persistent failure of scientists to shed light on the origins of genius, it would seem that, after all, Vasari's explanation may still be the best: "Occasionally, in a way that transcends nature, a single person is marvelously endowed by heaven with beauty, grace, and talent in such abundance that he leaves other men far behind, all his actions seem inspired, and indeed everything he does clearly comes from God rather than from human art."

different meaning becomes apparent. While discussing the proportions of the body, Leonardo wrote in his *Treatise on Painting*,

> For a man who knows how, it is easy to become universal, since all land animals resemble each other in the parts of their body, that is, muscles, nerves, and bones, and differ only in length and size.[3]

For Leonardo, in other words, being universal meant to recognize similarities in living forms that interconnect different facets of nature—in this case, anatomical structures of different animals. The recognition that nature's living forms exhibit such fundamental patterns was a key insight of the school of Romantic biology in the eighteenth century. These patterns were called *Urtypen* ("archetypes") in Germany, and in England Charles Darwin acknowledged that this concept played a central role in his early conception of evolution.[4] In the twentieth century, anthropologist and cyberneticist Gregory Bateson expressed the same idea in the succinct phrase "the pattern which connects."[5]

Thus, Leonardo da Vinci was the first in a lineage of scientists who focused on the patterns interconnecting the basic structures and processes of living systems. Today, this approach to science is called "systemic thinking." This, in my eyes, is the essence of what Leonardo meant by *farsi universale*. Freely translating his statement into modern scientific language, I would rephrase it this way: "For someone who can perceive interconnecting patterns, it is easy to be a systemic thinker."

## *LEONARDO'S SYNTHESIS*

Leonardo's synthesis of art and science becomes easier to grasp when we realize that in his time, these terms were not used in the sense in which we understand them today. To his contemporaries, *arte* meant skill (in the sense we still use today when we speak of "the art of medicine," or "the art of management"), while *scientia* meant knowledge, or theory. Leonardo insisted again and again that the "art," or skill, of painting must be supported by the painter's "science," or sound knowledge of

living forms, by his intellectual understanding of their intrinsic nature and underlying principles.

He also emphasized that this understanding was a continual intellectual process—*discorso mentale*—and that painting itself, therefore, deserved to be considered an intellectual endeavor.[6] "The scientific and true principles of painting," he wrote in the *Trattato*," are understood by the mind alone without manual operations. This is the theory of painting, which resides in the mind that conceives it."[7] This conception of painting sets Leonardo apart from other Renaissance theorists. He saw it as his mission to elevate his art from the rank of a mere craft to an intellectual discipline on a par with the seven traditional liberal arts. (In the Middle Ages, the seven branches of learning known as the liberal arts were the "trivium" of grammar, logic, and rhetoric, whose study led to the Bachelor of Arts degree, plus the "quadrivium" of arithmetic, geometry, astronomy, and music, which led to the Master of Arts.)

The third element in Leonardo's synthesis, in addition to *arte* (skill) and *scientia* (knowledge), is *fantasia*, the artist's creative imagination. In the Renaissance, confidence in the capabilities of the human individual had become so strong that a new conception of the artist as creator had emerged. Indeed, the Italian humanists were so bold as to compare artistic creations to the creations of God. This comparison was first applied to the creativity of poets, and was then extended, especially by Leonardo, to the painter's creative power:

> If the painter wants to see beauties that make him fall in love, he is the lord who can generate them, and if he wants to see monstrous things that frighten, or funny things that make him laugh, or things that truly arouse compassion, he is their lord and God. . . . In fact, whatever there is in the universe, by essence, presence, or imagination, he has it first in his mind and then in his hands.[8]

For Leonardo, the artist's imagination always remains closely linked to his intellectual understanding of nature. "The inventions of his *fantasia*," explains Martin Kemp, "are never out of harmony with universal

dynamics as rationally comprehended; they are fabulous yet not implausible, each element in their composition deriving from the causes and effects of the natural world."[9] At the same time, Leonardo insisted on the divine quality of the painter's creativity. "The godlike nature of the science of painting," he declared, "transforms the painter's mind into a resemblance of the divine mind."[10]

Leonardo realized that *fantasia* is not limited to artists, but rather is a general quality of the human mind. He called all human creations—artifacts as well as works of art—"inventions," and he made an interesting distinction between human inventions and the living forms created by nature. "Nature encompasses only the production of simple things," he argued, "but man from these simple things produces an infinity of compounds."[11]

From the modern scientific perspective, this distinction no longer holds, because we know that in the process of evolution, nature, too, produces living forms through an infinity of new compounds from cells and molecules. However, in a broader sense, Leonardo's distinction is still valid as a distinction between forms that emerge through evolution and forms created by human design. In contemporary scientific language, Leonardo's term "simple things" would be replaced by "emergent structures" and his notion of "compounds" by "designed structures."[12]

Throughout his life, Leonardo referred to himself as an inventor. In his view, an inventor was someone who created an artifact or work of art by assembling various elements into a new configuration that did not appear in nature. This definition comes very close to our notion of a designer, which did not exist in the Renaissance. (Leonardo's term *disegnatore*, sometimes incorrectly translated as "designer," always means "draftsman"; a better equivalent of "designer" is his term *compositore*.) The concept of design as a distinct profession emerged only in the twentieth century as a consequence of mass production and industrial capitalism.[13] During the preindustrial era, design was always an integral part of a larger process that included problem solving, innovation, form giving, decoration, and manufacturing. This process traditionally took place in the domains of engineering, architecture, crafts, and the fine arts.

Accordingly, Leonardo did not separate the design process—the

abstract configuration of multiple elements—from the process of material production. However, he always seemed to be more interested in the process of design than in its physical realization. It is worthwhile to recall that most of the machines and mechanical devices he invented, designed, and presented in superb drawings were not built; most of his military inventions and schemes of civil engineering were not realized; and although he was famous as an architect, his name is not connected with any known building. Even as a painter he often seemed to be more interested in the solution of compositional problems—the *discorso mentale*—than in the actual completion of the painting.

It seems to me, then, that the wide-ranging activities and achievements of Leonardo da Vinci, the archetypal *uomo universale*, are best examined within the three categories of artist, designer, and scientist. In his own synthesis, the activities of the inventor, or designer, like those of the artist, are inextricably linked to *scientia*, the knowledge of natural principles. He referred to himself, in one of his most arresting expressions, as "inventor and interpreter between nature and humans."[14]

## *THE SUBLIME LEFT HAND*

In practice, it was Leonardo's exceptional drawing facility that formed the link between the three domains of art, design, and science, as he himself recognized:

> Drawing, [the foundation of painting], teaches the architect to render his building agreeable to the eye; this is what teaches potters, goldsmiths, weavers, embroiderers. It has found the characters by which different languages are expressed; it has given the arithmeticians their ciphers and has taught geometers how to represent their figures; it instructs the experts in perspective, astronomers, machine builders, and engineers.[15]

With his acute powers of observation and his "sublime left hand" (as his friend, the mathematician Luca Pacioli, called it), Leonardo was able to draw, in exquisite detail, flowers, birds in flight, whirlpools, muscles and bones, and human expressions with unparalleled accuracy

*Figure 2-1: Madonna and Child and other studies, c. 1478–80, Drawings and Miscellaneous Papers, Vol. III, folio 162r*

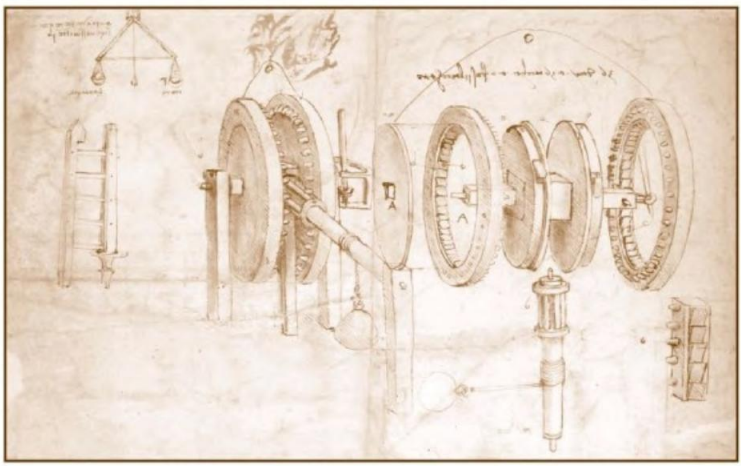

*Figure 2-3: Two-wheeled hoist, Codex Atlanticus, folio 30v*

historian Daniel Arasse points out, while theirs are merely explanatory, Leonardo's are *convincing*, persuading the viewer of the feasibility and soundness of the author's designs:

> His working drawings not only possess a rare elegance; they are visually put in context, and they have the concrete appearance of objects which exist: the angle or angles of view, the subtlety of the shadows and the treatment of the background itself on which they are drawn gives them an extraordinarily persuasive . . . effectiveness.[20]

As an artist, Leonardo introduced a novelty into the practice of preparatory drawing, which forms an intriguing counterpoint to the precision of his scientific and technical drawings.[21] In many studies for his paintings, he would go over the outlines of a figure again and again, sketching several alternative lines and variations of the figure's position, until he found the ideal form. These preparatory sketches have an extraordinary dynamic quality. One can almost feel the rhythm of Leonardo's "sublime left hand" as he tries out different possibilities,

translating his *discorso mentale* into a blur of lines. In Leonardo's time, this technique was unprecedented, as Martin Kemp describes:

> Never before had any artist worked out his compositions in such a welter of alternative lines. The pattern-book drawing techniques of the fourteenth and fifteenth centuries, which Verrocchio had relaxed in some measure, have here been overthrown in a "brain storm" of dynamic sketching. Such flexibility of preparatory sketching became the norm for later centuries; it was introduced almost single-handedly by Leonardo.[22]

Sometimes—as, for example, in a study for his famous *Madonna and Child with Saint Anne*—Leonardo would push his technique of dynamic sketching to an extreme, producing what Arasse describes as "an unreadable blur. Nothing can any longer be distinguished in this chaos, but his eye has perceived in the movement of his hand the hidden, buried, latent form, straining to become a figure. Leonardo marks this with a stylus and, turning the sheet over, makes it visible with a distinct line."[23]

To me, this is a fascinating visual illustration of the process known to complexity theorists as "emergence"—the spontaneous emergence of new forms of order out of chaos and confusion.[24] According to complexity theory, creativity—the generation of new forms—is a key property of all life, and it involves the very process that Leonardo revealed in his exquisite preparatory drawings. I would argue that our most creative insights emerge from such states of uncertainty and confusion.

## *THE SOUL OF PAINTING*

Although he kept his scientific ideas to himself, Leonardo freely shared his views on painting with his students and fellow artists. At his death he left over six hundred pages of detailed instructions for painters, covering all aspects of his science and art of painting. From this vast collection, scattered through eighteen of Leonardo's Notebooks (over half of which, as noted earlier, are now lost), his friend and disciple

*Figure 2-4:* Virgin of the Rocks, *c. 1483–86, Musée du Louvre, Paris*

only revolutionary in its rendering of light and dark. It also represented a complex and controversial meditation on the destiny of Christ, expressed through the gestures and relative positions of the four protagonists, as well as in the intricate symbolism of the surrounding rocks and vegetation.[44]

The rocks themselves are rendered with astounding geological accuracy. Leonardo depicted a complex geological formation involving soft, weathered sandstone dissected by a layer of harder rock known to geologists as diabase. Numerous fine details in the rocks' textures and weathering patterns show the artist's profound knowledge, unmatched in his time, of such geological formations.[45] And finally—in a dramatic departure from the traditional decorative use of plants in the quattrocento—the plants growing in the surroundings of the rocky grotto are rendered not only in exquisite botanical detail but also in their proper habitat, with complete seasonal and ecological accuracy.[46]

Observations of similar innovations can be made in *The Last Supper*, the *Mona Lisa*, or the *Madonna and Child with Saint Anne*. It is no wonder that each of these masterpieces caused great commotion among Leonardo's contemporaries, generating animated discussions and numerous copies, which expanded the master's *discorso mentale* throughout Europe's artistic and intellectual circles.

## *IL CAVALLO*

In the "Paragone," Leonardo introduces one of his lengthy arguments about the superiority of painting over sculpture with the following self-assured words:

> As I apply myself in sculpture no less than in painting, and practice both in the same degree, it seems to me that without being suspected of unfairness I can judge which of the two is of greater ingenuity and of greater difficulty and perfection.[47]

In a similar vein, Vasari refers to Leonardo as "Florentine painter and sculptor" in the title of his biography. And yet, we have no known sculpture from Leonardo's hand. His reputation as a sculptor rests on a

visited the princely stables of Ludovico as well as those of other wealthy Milanese noblemen in search of models for his *cavallo*. He identified several superb thoroughbreds, measured them meticulously to determine their proportions, and drew them from life in numerous positions. In typical fashion, he got carried away with the intellectual aspects of the undertaking, expanded it into a major research project, and ended up with a full treatise on the anatomy of the horse.[51] In addition, he produced a wealth of artistic studies of horses, now assembled in a special volume of the Royal Collection at Windsor Castle. In the opinion of art critic Martin Kemp, "No one has ever captured more convincingly the rippling beauty of a finely bred and groomed horse."[52]

Finally, after four years of preparatory studies, Leonardo built a full-scale model of the sculpture out of clay. At a height of slightly over twenty-three feet, it towered over the most famous equestrian statues of the time—that of Marcus Aurelius on the Capitol in Rome, Donatello's *Gattamelata* in Padua, and Verrocchio's *Colleoni* in Venice. Not surprisingly, the colossal model generated enormous excitement when it was displayed in front of the Sforza castle on the occasion of the marriage of Ludovico's niece Bianca Maria to the emperor Maximilian. "The vehement, life-like action of this horse, as if panting, is amazing," wrote Paolo Giovio, "not less so the sculptor's skill and his consummate knowledge of nature." Vasari claimed that those who saw the clay model felt that they had never seen a more magnificent piece of work. The court poets composed Latin epigrams in praise of the *gran cavallo*, and Leonardo's fame as a sculptor soon spread throughout Italy.

While completing the model, Leonardo thought deeply about the tremendous challenge of casting such a large piece. He collected all his notes on the subject in seventeen folios of a book (now bound at the end of the Codex Madrid II), beginning with the words: "Here a record shall be kept of everything related to the bronze horse presently under construction."[53]

The traditional method of casting was to divide the work into several smaller pieces to be cast separately, but Leonardo concluded that it would not be possible to make all the pieces of uniform thickness. As a result, he would not be able to estimate their weight and establish in advance the overall balance of the sculpture. Having investigated all aspects of the problem with his usual attention to meticulous details,