An Excerpt From

Learning from Leonardo
Decoding the Notebooks of a Genius

by Fritjof Capra

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LEARNING FROM LEONARDO

Fritjof Capra

BESTSELLING AUTHOR OF *THE TAO OF PHYSICS* AND *THE WEB OF LIFE*

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Facing: Botanical specimen from "Star of Bethlehem," c. 1508 (detail, see plate 6).

Page vi: Studies of flexions of the spine in the movements of horses, cats, and dragons, c. 1508 (detail, see fig. 6-3).

To my brother Bernt
who has shared my fascination
with the genius of Leonardo da Vinci
from the very beginning

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PREFACE

In his classic *Lives of the Artists*, the Italian painter and architect Giorgio Vasari said of Leonardo da Vinci:

> 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.

Indeed, during the Renaissance Leonardo was renowned as an artist, engineer, and inventor throughout Italy, France, and other European countries. In the centuries after his death, his fame spread around the world, and it continues undiminished to this day.

I have been fascinated by the genius of Leonardo da Vinci for several decades and have spent the last ten years studying his scientific writings in facsimile editions of his famous Notebooks. My first book about him, *The Science of Leonardo*, published in 2007, is an introduction to his life and personality, his scientific method, and his synthesis of art and science. In this second book I go a step further, presenting an in-depth discussion of the main branches of Leonardo's scientific work from the perspective of twenty-first-century science—his fluid dynamics, geology, botany, mechanics, science of flight, and anatomy. Most of his astonishing discoveries and achievements in these fields are virtually unknown to the general public.

Leonardo da Vinci was what we would call, in today's scientific parlance, a systemic thinker. Understanding a phenomenon, for him, meant connecting it with other phenomena through a similarity of patterns. He usually worked on several projects in parallel, and when his understanding advanced in one area he would revise his ideas in related areas accordingly.

Thus, to appreciate the full extent of his genius, one needs to be aware of the evolution of his thinking in several parallel but interconnected disciplines. This has been my approach to absorbing and understanding Leonardo's scientific thought. Having explored and contributed to the systems view of life that has emerged in science in the last thirty years, and having written several books about it, I found it very natural to analyze and interpret Leonardo's science from that perspective. Indeed, I believe that the ever-present emphasis on relationships, patterns, qualities, and transformations in his writings, drawings, and paintings—the tell-tale sign of systemic thinking—was what initially attracted me to his work and kept me utterly fascinated for so many years.

What emerged from my explorations of all the branches of Leonardo's science and of his "demonstrations" (as he called them) in his drawings, paintings, and writings was the realization that, at the most fundamental level, Leonardo always sought to understand the nature of life. His science is a science of living forms, and his art served this persistent quest for life's inner secrets. In order to paint nature's living forms, Leonardo felt he needed a scientific understanding of their intrinsic nature and underlying principles; in order to analyze the results of his observations, he needed his artistic ability to depict them. I believe that this intersection of needs is the very essence of his synthesis of science and art.

Leonardo thought of himself not only as an artist and natural philosopher (as scientists were called in his time), but also 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 modern notion of a designer, which did not exist in the Renaissance. Indeed, I have come to believe that the wide-ranging activities of Leonardo da Vinci, the archetypal Renaissance man, are best examined within the three categories of art, science, and design. In all three dimensions he uses living nature as his mentor and model. In fact, as I delved into the Notebooks, I discovered not only Leonardo the systemic thinker but also, to my great surprise, Leonardo the ecologist and ecodesigner.

The persistent endeavor to put life at the very center of his art, science, and design, and the recognition that all natural phenomena are fundamentally interconnected and interdependent, are important lessons we can learn from Leonardo today. Thus, Leonardo's synthesis is not only intellectually fascinating but also extremely relevant to our time, as I shall argue in the Coda of this book.

In previous decades, scholars of Leonardo's Notebooks tended to see them as disorganized and chaotic. My own sense, however, is that in Leonardo's mind, his science was not disorganized at all. In his manuscripts, we find numerous reminders to himself as to how he would eventually integrate the entire body of his research into a coherent whole. I have tried to follow these clues, arranging the material of this present book in a framework that I feel is consistent with Leonardo's thought. In fact, several of my chapter titles—"The Movements of Water," "The Elements of Mechanics," "The Human Figure"—are the ones Leonardo himself intended to use.

Leonardo's view of natural phenomena is based partly on traditional Aristotelian and medieval ideas and partly on his independent and meticulous observations of nature. The result is a unique science of living forms and their continual movements, changes, and transformations—a science that is radically different from that of Galileo, Descartes, and Newton.

A fundamental underlying idea is that nature as a whole is alive, and that the patterns and processes in the macrocosm of the Earth are similar to those in the microcosm of the human body. I have divided the contents of Leonardo's scientific work into these two basic categories: nature's forms and transformations in the macrocosm and in the microcosm. They constitute Parts I and II of the present book.

In the macrocosm, the main themes of Leonardo's science are the movements of water and air (chapter 1), the geological forms and transformations of the living Earth (chapter 2), and the botanical diversity and growth patterns of plants (chapter 3). In the microcosm, his main focus was on the human body—its beauty and proportions (chapter 4), the mechanics of its movements (chapter 6), and how it compared to other animal bodies in motion, in particular the flight of birds (chapter 7).

Unlike Descartes, Leonardo did not see the body as a machine, but he clearly recognized that the anatomies of animals and humans involve mechanical functions that can be appreciated only with an understanding of the basic principles of mechanics. Consequently, he reminded himself to "arrange it in such a way that the [chapter] on the elements of mechanics with its practice shall precede the demonstration of the movement and force of man and other animals." I have followed Leonardo's advice. My chapter on "The Elements of Mechanics" (chapter 5) precedes that on "The Body in Motion" (chapter 6).

As I have mentioned, Leonardo's ultimate goal—in his science as well as his art—was to understand the nature of life. This persistent quest culminated in his anatomies of the heart and blood vessels and in the embryological studies he undertook in his old age. Leonardo's explorations of the mystery of life in the human body (chapter 8) are the final highlight of my analysis of his science.

To follow Leonardo's meandering mind as he moves swiftly between interrelated phenomena—for example, from patterns of turbulence in water to similar patterns in the flow of air, the flight of birds, and on to the nature of sound and the design of musical instruments—is not easy within the linear constraints of written language. I have tried to facilitate this task by including in my text a network of cross-references, as well as copious references to Leonardo's manuscripts and to the works of the foremost Leonardo scholars. In addition, I have compiled a short chronology of Leonardo's life and work (see p. 326), which shows how he was constantly involved in several simultaneous projects.

In this and in my previous book, I discuss more than one hundred scientific discoveries made by Leonardo da Vinci during the fifteenth and sixteenth centuries. In the following pages, I present a timeline of his fifty or so most important discoveries, together with indications of the centuries when they were rediscovered by other scientists. This graphic summary is an impressive reminder of Leonardo's pioneering genius in so many scientific fields.

Leonardo did not publish any of his discoveries, nor do we have any records of written correspondence with the natural philosophers, mathematicians, engineers, doctors, and other intellectuals with whom he maintained regular contact. Although we can assume that he shared some of his insights and working methods in conversations with this circle, we have no evidence of any direct influence of his scientific achievements on subsequent generations of scientists.

Today, as we are developing a new systemic understanding of life with a strong emphasis on complexity, networks, and patterns of organization, we are witnessing the gradual emergence of a science of qualities that has some striking similarities with Leonardo's science of living forms. We cannot help but wonder how Western science might have developed had

Leonardo's Notebooks been studied by the founders of the Scientific Revolution in the seventeenth century.

From their correspondence it is evident that Galileo, Newton, and their contemporaries struggled with many of the same problems that Leonardo had recognized and often solved one or two centuries earlier. Moreover, they used similar metaphors and reasoned in similar ways, so they would have understood his Notebooks much better than we do today. If they had been aware of his discoveries, the development of science would doubtless have taken a very different path, and Leonardo da Vinci's influence on scientific thought might have been as profound as his impact on the history of art.

Fritjof Capra
Berkeley
February 2013

TIMELINE OF SCIENTIFIC DISCOVERIES

The following chart lists the most important scientific discoveries made by Leonardo da Vinci during the fifteenth and sixteenth centuries, together with the approximate dates when they were rediscovered by other scientists. It also includes references to the pages of this book (in parentheses) where the discoveries are discussed, as well as corresponding page references [in brackets] to my previous book, *The Science of Leonardo*.

Discovered by Leonardo between 1485 and 1515

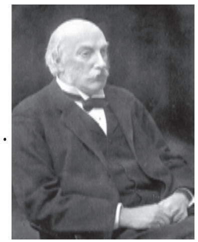
1500 1600 1700 1800 1900 2000

OPTICS

Wave nature of light
[p. 231]

CHRISTIAAN HUYGENS
(c. 1678)

Rayleigh scattering
(why the sky is blue)
[p. 233]



LORD RAYLEIGH
(c. 1871)

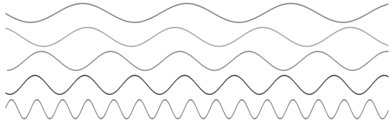
1500 1600 1700 1800 1900 2000

Discovered by
Leonardo between
1485 and 1515

	1500	1600	1700	1800	1900	2000

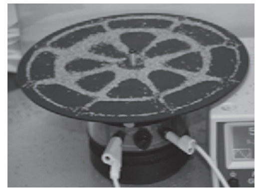
ACOUSTICS

Wave nature of sound .... MARIN MERSENNE (c. 1636)
[p. 231]



Chladni patterns ....
(dust on vibrating plates)
[p. 235]

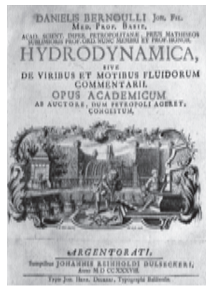
ERNST CHLADNI
(c. 1787)



FLUID DYNAMICS

Universality of flow ....
(regardless of substance)
(p. 33)

DANIEL BERNOULLI
(c. 1738)


DANIELIS BERNOULLI
HYDRODYNAMICA,
SIVE
DE VIRIBUS ET MOTIBUS FLUIDORUM
COMMENTARII.
OPUS ACADEMICUM
AB AUCTORE, DUM PETROPOLI AGERET,
CONGESTUM.
ARGENTORATI,

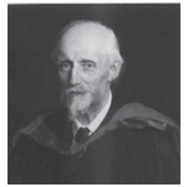
	1500	1600	1700	1800	1900	2000

Discovered by Leonardo between 1485 and 1515

1500 | 1600 | 1700 | 1800 | 1900 | 2000

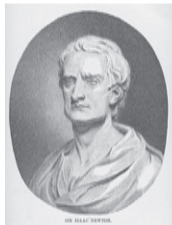
FLUID DYNAMICS

Flow visualizations (millet grains, dye, etc.) (p. 35)



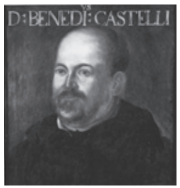
OSBORNE REYNOLDS
(c. 1883)

Viscosity (p. 42)



ISAAC NEWTON
(c. 1687)

Continuity principle (conservation of mass) (p. 45)



BENEDETTO CASTELLI
(c. 1628)

1500 | 1600 | 1700 | 1800 | 1900 | 2000

Discovered by
Leonardo between
1485 and 1515

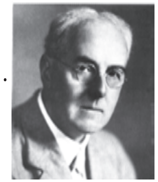
1500 1600 1700 1800 1900 2000

FLUID DYNAMICS

Dynamics of water vortex (p. 47)

HERMANN VON HELMHOLTZ
(c. 1858)

Richardson cascade (vortices of decreasing scales) (p. 50)



LEWIS RICHARDSON
(c. 1922)

Reynolds turbulence decomposition (p. 53)

OSBORNE REYNOLDS
(c. 1895)

1500 1600 1700 1800 1900 2000

Discovered by Leonardo between 1485 and 1515

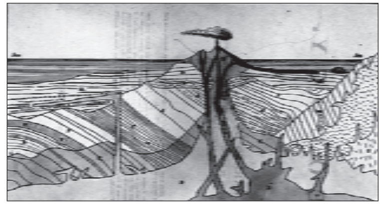
1500 | 1600 | 1700 | 1800 | 1900 | 2000

GEOLOGY

Superposition of rock strata (p. 75)

NICOLAS STENO (c. 1669)

Great duration of geological time (p. 74)



CHARLES LYELL (c. 1830–33)

Nature of fossils (p. 81)

NICOLAS STENO (c. 1669)

Growth rings on fossil shells, used to determine age (p. 84)

D.W. KNUTSON (c. 1974)

Rock cycle (erosion, sedimentation, uplift, erosion) (p. 92)

JAMES HUTTON (c. 1785)

1500 | 1600 | 1700 | 1800 | 1900 | 2000

Discovered by Leonardo between 1485 and 1515

1500 | 1600 | 1700 | 1800 | 1900 | 2000

BOTANY

Foundation of plant morphology and plant physiology (p. 113)

JOHANN WOLFGANG VON GOETHE (c. 1790)

Branching patterns linked to nutrient flow (p. 116)

F. WENT (c. 1928)

Contribution of sunlight to plant growth (p. 119)

JAN INGENHOUSZ (c. 1779)

Contribution of air to plant growth (p. 120)

JEAN SENEBIER (c. 1779)

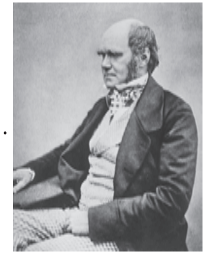
1500 | 1600 | 1700 | 1800 | 1900 | 2000

Discovered by
Leonardo between
1485 and 1515

1500 1600 1700 1800 1900 2000

BOTANY

Tropism (orientation of plants in response to stimuli) (p. 120) ······

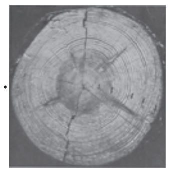


CHARLES DARWIN
(c. 1880)

Regulation of plant growth by hormones ("vital sap") (p. 120) ······ P. BOYSEN-JENSEN (c. 1913)

Migration of sap (auxins) from light to dark side of stem (p. 123) ······ F. WENT (c. 1928)

Annual growth rings, linked to wet and dry years (p. 121) ······



A.E. DOUGLAS
(c. 1937)

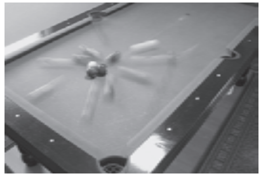
1500 1600 1700 1800 1900 2000

Discovered by
Leonardo between
1485 and 1515

1500 1600 1700 1800 1900 2000

MECHANICS

Relativity of motion (p. 177)



CHRISTIAAN HUYGENS
(c. 1656)

Anticipation of conservation of energy (p. 183)

JAMES JOULE
(c. 1840)

Definition of force of friction (p. 186)

CHARLES COULOMB
(c. 1785)

Energy dissipation (p. 187)

SADI CARNOT
(c. 1824)

1500 1600 1700 1800 1900 2000

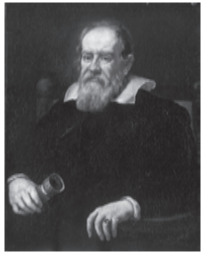
Discovered by
Leonardo between
1485 and 1515

1500 | 1600 | 1700 | 1800 | 1900 | 2000

MECHANICS

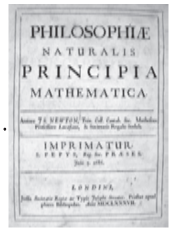
ARTHUR EDDINGTON
(c. 1928)

Anticipation of “arrow of time” (irreversible processes) (p. 188)



GALILEO GALILEI
(c. 1609)

Parabolic nature of ballistic trajectories (p. 196)



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA

IMPRIMATUR

LONDINI,

ISAAC NEWTON
(c. 1687)

Newton’s third law of motion: action = reaction (p. 200)

1500 | 1600 | 1700 | 1800 | 1900 | 2000

Discovered by Leonardo between 1485 and 1515

1500 1600 1700 1800 1900 2000

AERODYNAMICS

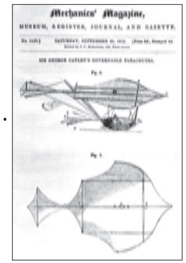
Aerodynamics: the proper basis for a science of flight (p. 265)

GEORGE CAYLEY (c. 1809)

Principle of the wind tunnel (p. 266)

FRANCIS WENHAM (c. 1871)

Density distribution around a bird wing (p. 267)


Mechanics' Magazine,
MUSEUM, REGISTER, JOURNAL, AND GAZETTE.

GEORGE CAYLEY (c. 1810)

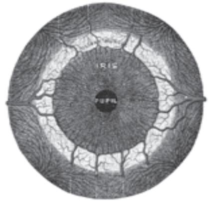
1500 1600 1700 1800 1900 2000

Discovered by Leonardo between 1485 and 1515

1500 | 1600 | 1700 | 1800 | 1900 | 2000

HUMAN ANATOMY

Sphincter of the pupil [p. 240] .... FREDERIK RUYSCH (c. 1691)



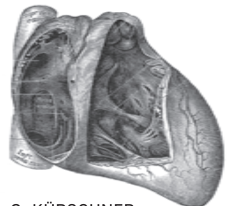
FREDERIK RUYSCH
(c. 1691)

Atria of the heart (p. 291) .... WILLIAM HARVEY (c. 1628)

WILLIAM HARVEY
(c. 1628)

Systole as the active movement of the heart (p. 294) .... WILLIAM HARVEY (c. 1628)

Papillary muscles and their tendons (p. 292) .... G. KÜRSCHNER (c. 1850)



G. KÜRSCHNER
(c. 1850)

Discovery of aortic sinuses (sinuses of Valsalva) (p. 300) .... ANTONIO VALSALVA (c. 1710)

ANTONIO VALSALVA
(c. 1710)

1500 | 1600 | 1700 | 1800 | 1900 | 2000

Discovered by Leonardo between 1485 and 1515

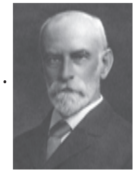
1500	1600	1700	1800	1900	2000

HUMAN ANATOMY

Gradual closure of aortic valve by blood turbulence (p. 301) .... C. LEE AND L. TALBOT (c. 1979)

Discovery and explanation of arteriosclerosis (p. 307) .... JEAN LOBSTEIN (c. 1833)

Definition of living organisms as open systems (p. 311) .... LUDWIG VON BERTALANFFY (c. 1940)

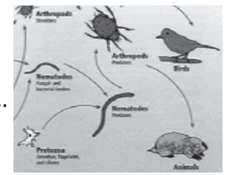


Quantitative observations of fetal growth (p. 316) .... CHARLES MINOT (c. 1892)

Development of the embryo's mental life (p. 318) .... HUMBERTO MATURANA (c. 1970)

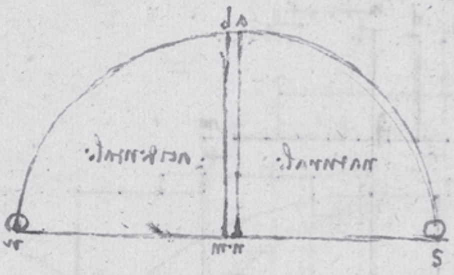
ECOLOGY

Anticipation of food chains and food cycles (p. 282) ....



CHARLES ELTON (c. 1927)

1500	1600	1700	1800	1900	2000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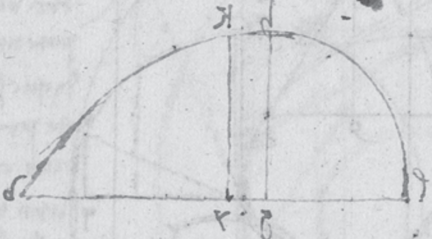
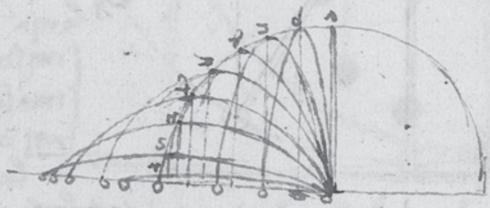
naturale


naturale
accidentale





PROLOGUE

Leonardo's Genius

Before entering into the details of Leonardo's science, let us examine what is commonly referred to as his genius.

During Leonardo's time, the term "genius" did not have our modern meaning of a person endowed with extraordinary intellectual and creative powers.[1] 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, denoting 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 has been recognized throughout the ages. It has often been associated with divine inspiration, attributed first to poets and later on also to painters and other artists. In the Italian Renaissance, those individuals were given 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 genetics, 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 estab-

FACING Studies of the motion of a pendulum.
Codex Madrid I, folio 147r (detail, see fig. 5-14).

lish some common pattern.[2] 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.

However, psychologists have been able to identify a set of mental attributes that, in addition to exceptional talent in a particular field, seem to be distinctive signs of genius.[3] All these were characteristic of Leonardo to a very high degree. Identifying these signs of genius in the mind and working methods of Leonardo da Vinci is an exercise that can inspire our own lives, both as individuals and as a society.

Relentless Curiosity and Intellectual Fearlessness

The first distinctive characteristic of a genius is an intense curiosity and great enthusiasm for discovery and understanding. This was indeed an outstanding quality of Leonardo, whom art historian Kenneth Clark called "the most relentlessly curious man in history."[4] Throughout Leonardo's life, this boundless curiosity was his main driving force. Wherever he looked, there were new discoveries to be made, and for forty years he explored almost the entire range of natural phenomena known in his time, as well as many others previously unknown.

This curiosity was matched by incredible mental energy, so much so that following the trains of thought in Leonardo's Notebooks can be quite exhausting.[5] As I did so over the years, I was struck again and again by the fact that he never seemed to have the slightest hesitation about entering into new fields of knowledge. In the chapter on geology (chapter 2), this is illustrated in some detail with Leonardo's extensive research on fossils. I offer it here as an example of his intellectual fearlessness.

Marine fossils represented an enigma to Leonardo that natural philosophers had debated intensely since antiquity. If fossil shells were remnants of marine organisms, how did they end up in sedimentary strata that lie in the high mountains? Leonardo studied a wide variety of fossils with the utmost care, precisely described their specific sites, and reconstructed the process of fossilization in remarkable detail. He also studied the classical texts and then set out to refute the theories current in his time, the most popular being that the fossil shells had been carried to the mountains from the sea by the biblical flood.

Based on highly sophisticated observations, Leonardo presented several brilliant arguments that invalidated this and other theories involving supernatural forces and showed convincingly that the fossils found in mountain rocks had been formed in the oceans where these creatures had lived in the distant past. Having done so, however, he still had to show how those layers of marine sediments ended up in the high mountains. In other words, he needed to posit a theory of how mountains were formed during extremely long periods of geological time.

Leonardo did not hesitate to take on this formidable challenge. Again he studied the principal classical and medieval texts, this time on the formation of the Earth, and he used some of their key ideas to formulate his own tectonic theory—an elaborate blend of Aristotelian and medieval ideas, combined with his own observations and with astonishing conceptions that are not unlike those of our modern plate tectonics.

In all these endeavors, Leonardo attempted to explain the phenomena he investigated in terms of natural processes. He scoffed at any belief in supernatural forces, repeatedly referred to nature (instead of God) as the source of all creation, and held a firm belief that nature's creations could be understood rationally, while also acknowledging the limitations of the human mind.

Intense Concentration and Attention to Detail

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."[6] Leonardo seems to have worked in a very similar way, most of the time not on just one but on several problems simultaneously.

Leonardo combined his powers of concentration with tremendous patience. He might let weeks pass between putting successive layers of paint on an oil painting, and would rework and refine his panels for years, reflecting on every detail of their conception, engaging with himself in what he called a "mental discourse" (*discorso mentale*). He showed the same patience and attention to detail in his scientific observations and experiments.

Holistic Memory

Closely associated with the power of intense concentration that is characteristic of geniuses seems to be their exceptional holistic memory—an ability to memorize large amounts of information in the form of a coherent whole, a single gestalt. 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. Mozart, as a child, wrote out a note-perfect score of a complex choral composition after hearing it only once. Leonardo would follow people with striking facial features for hours, memorize their appearance, and then draw them, reportedly with complete accuracy, when he was back in his studio.

We have a vivid testimony of Leonardo's exceptional powers of concentration, his great patience, and his holistic memory from a contemporary writer, 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, 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.[7]

The mental attributes discussed so far—relentless curiosity, intellectual fearlessness, a capacity for intense concentration, attention to detail, and holistic memory—are characteristics of genius that seem to be timeless, independent of historical and cultural contexts. In addition, Leonardo displayed signs of genius that can only be appreciated within the historical context of the Middle Ages and the Renaissance. Two of these in particular are defining characteristics of his scientific thought: his empirical method and his systemic thinking.

Leonardo's Empirical Method

In the mid-fifteenth century, when the young Leonardo received his training as a painter, sculptor, and engineer in Florence, science in the modern sense, as a systematic empirical method for gaining knowledge about the natural world, did not exist. The worldview of natural philosophy, as it was then called, had been handed down from Aristotle and other philosophers of antiquity and then fused with Christian doctrine by the Scholastic theologians who presented it as the officially authorized creed. The religious 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:

> 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.[8]

One hundred years before Galileo Galilei and Francis Bacon, Leonardo 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.[9] In the intellectual history of Europe, Galileo, 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, which were complemented by great drawing skills. He was able to draw the complex swirls of turbulent water or the swift movements of a bird in flight with a precision that would not be reached again until the invention of serial photography.

What turned Leonardo from an artist 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. This is exactly what Leonardo did. He never tired of repeating his experiments and observations again and again, with fierce attention to the minutest detail, and he would often systematically vary his parameters to test the consistency of his results.

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. After testing the traditional ideas repeatedly with careful observations and experiments, Leonardo would adhere to tradition if he found no contradictory evidence; but if his observations told him otherwise he would not hesitate to formulate his own alternative explanations.

As I have mentioned, Leonardo generally worked on several problems simultaneously and paid special attention to similarities of patterns in different areas of investigation. When he made progress 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 practice 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 tentative theoretical models that are characteristic of modern science. For example (as discussed in chapter 8), he proposed several different models for the functioning of the heart and its role in maintaining the flow of blood before he concluded that the heart is a muscle pumping blood through the arteries.

Leonardo also used simplified models—or approximations, as we would say today—to analyze the essential features of complex phenomena. For instance, he represented the flow of water through a channel of varying cross section by using a model of rows of men marching through a street of varying width (see chapter 1). This technique of using simplified theoretical models to understand complex phenomena put him centuries ahead of his time.

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 works 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 a 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.

Since the Scientific Revolution in the seventeenth century, this progress in science has been a collective enterprise. Scientists continually exchange letters, papers, and books and discuss their theories at various meetings and conferences. With Leonardo, the situation was quite different. He worked alone and in secrecy, did not publish any of his findings, and only rarely dated his notes. Having pioneered the scientific method in solitude, he did not see science as a collective, collaborative enterprise. Leonardo's secrecy about his scientific work is the one significant respect in which he was not a scientist in the modern sense.

Systemic Thinking

Throughout the history of Western science, there has been a basic conceptual tension between the parts and the whole. The emphasis on the parts has been called mechanistic, reductionist, or atomistic; the emphasis on the whole holistic, organismic, or ecological. In twentieth-century science, the holistic perspective has become known as "systemic" and the way of thinking it implies as "systemic thinking."

At the dawn of Western philosophy and science, Pythagoras distinguished "number," or pattern, from substance, or matter, viewing it as something that limits matter and gives it shape. Ever since the days of early Greek philosophy, there has been this tension between substance and pattern, between matter and form. The study of matter begins with the question, "What is it made of?" This leads to the notion of fundamental elements, building blocks that can measured and quantified. The study of form asks, "What is the pattern?" And that leads to the notions of order, organization, relationships. Instead of quantity, it involves quality; instead of measuring, it involves mapping.

These two very different lines of investigation have been in competition with one another throughout our scientific and philosophical tradition. The study of matter was championed by Democritus, Galileo, Descartes, and Newton; the study of form by Pythagoras, Aristotle, Kant, and Goethe. Leonardo clearly followed the tradition of Pythagoras and Aristotle in developing his science of living forms, their patterns of organization, and their processes of growth and transformation. Indeed, systemic thinking lies at the very core of his approach to scientific knowledge.

Leonardo's science is 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.

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. At the most fundamental level, as already mentioned, Leonardo always sought to understand the nature of life. This has often escaped earlier commentators, 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 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.

Leonardo's studies of the living forms of nature began with their appearance to the painter's eye and then proceeded to detailed investigations of their intrinsic nature. His science is a science of qualities. He preferred to *depict* the forms of nature rather than *describe* their shapes, and he analyzed them in terms of their proportions rather than measured quantities.

Another important aspect of systems science is its inherently dynamic nature. Since the earliest days of biology, scientists and philosophers have recognized that living form is more than shape, more than a static configuration of components in a whole. There is a continual flow of matter through a living system, while its form is maintained; there is growth and decay, regeneration and development. Hence, the understanding of living structure is inextricably linked to the understanding of metabolic and developmental processes.

This was very much Leonardo's approach. His science is utterly dynamic. He portrays nature's forms—in mountains, rivers, plants, and the human body—in ceaseless movement and transformation. 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 development and flux, in which all configurations and forms are merely stages in a continual process of transformation.

Inspiration for Our Time

Here, then, are the principal signs of Leonardo's genius: his relentless curiosity, intellectual fearlessness, capacity for intense concentration, attention to detail, holistic memory, commitment to the empirical method, and pervasive systemic thinking. Most of us will not be able to develop these characteristics of genius to anywhere near Leonardo's degree. But we can all be inspired by his specific ways of work—as a scientist, artist, and designer—and learn valuable lessons from his method.

The great challenge of our time is to build and nurture sustainable communities—communities designed in such a way that their ways of life, businesses, economy, physical structures, and technologies respect, honor, and cooperate with nature's inherent ability to sustain life. The first step in this endeavor, naturally, must be to understand how nature sustains life. It turns out that this involves a new ecological understanding of life, also known as "ecological literacy," as well as the ability to think systemically—in terms of relationships, patterns, and context.

Indeed, such a new understanding of life has emerged over the last thirty years.[10] Contemporary science no longer sees the universe as a machine composed of elementary building blocks. We have discovered that the material world, ultimately, is a network of inseparable patterns of relationships; the planet as a whole is a living, self-regulating system. The view of the human body as a machine and of the mind as a separate entity is being replaced by one that sees not only the brain but also the immune system, the bodily tissues, and even each cell as a living, cognitive system. Evolution is seen not as a competitive struggle for existence, but rather as a cooperative dance in which creativity and the constant emergence of novelty are the driving forces. With the new emphasis on complexity, networks, and patterns of organization, a new science of qualities is slowly emerging.

This new science is being formulated in a language quite different from Leonardo's. As we shall see throughout this book, however, the underlying conception of the living world as being fundamentally interconnected, highly complex, creative, and imbued with cognitive intelligence is quite similar to Leonardo's vision. This is the main reason, in my view, why the science and art of this great genius of the Renaissance can be a tremendous inspiration for our time.

The new systemic understanding of life that has been developed at the forefront of science comprises biological, cognitive, social, and ecological dimensions. It applies to all living systems—individual organisms, social systems, and ecosystems. Hence, it is relevant to virtually all professions and endeavors, besides being fascinating in itself. Our intellectual curiosity to find out more about it may encounter demanding obstacles at first, but in the end will be richly rewarded.

At the core of the new understanding of life is a shift of metaphors from seeing the world as a machine to understanding it as a network. Exploring this shift without prejudice, driven by intellectual curiosity, will be beneficial in many ways. Individually, it will help us to better deal with our health, seeing our organism as a network of components with both physical and cognitive/emotional dimensions. As a society, the exploration of networks will help us to build a sustainable future, grounded in the awareness of ecological networks and the interconnectedness of our major problems. Such exploration will also help us manage our organizations, which are social networks of increasing complexity.

We may not be able to match Leonardo's capacity for intense concentration and attention to detail over long periods of time, but we will be more successful in dealing with the challenges of the frenetic pace of our Industrial Age if we give ourselves adequate time to reflect on a problem, keeping in focus both the problem and its various ramifications. Creating extended periods of time for reflection in order to carefully think through our solutions before applying them is what environmental educator David

Orr calls "slow knowledge"—the equivalent of Leonardo's *discorso mentale*.[11] In our human organizations, the challenge will be to create these periods of reflection for the benefit of all members and the organization as a whole.

Very few people have the capacity for what I have called "holistic memory"—the ability to memorize large amounts of information in the form of a coherent whole. But we all can train ourselves to improve our associative memory, to remember relationships and connections, which is crucial for systemic thinking. Today, with information at our fingertips in our laptops and smart phones, what is important is to know how things are interconnected rather than to remember individual facts exactly. As the great playwright and statesman Václav Havel put it: "Education is the ability to perceive the hidden connections between phenomena."[12]

Leonardo developed his empirical method single-handedly, in a cultural vacuum. Today, the scientific method is practiced worldwide, but it is still ignored or even rejected by many individuals and institutions outside of science. This is true, for example, of many conservative politicians in the United States, who are often ignorant or in denial of the scientific facts about climate change, or even about evolution. We will all be much better off, as individuals and as a society, if we respect the empirically based and carefully honed insights of scientists and act accordingly.

As I have mentioned, Leonardo was always respectful of the classical Greek and Latin texts and familiarized himself with them as much as possible, accumulating a considerable personal library and often borrowing manuscripts from other scholars. He would usually start his investigations from commonly accepted concepts and explanations, but then always proceeded to examine the classics critically, never afraid of correcting them in the light of his own observations.

As we develop our ability to think systemically, together with our creativity and intuition, we need to be aware of the constant interplay between tradition and innovation. We need new ideas for many of our systemic problems, but we also need to be educated—that is, familiar with tradition—to even formulate our questions and to avoid reinventing the wheel. Leonardo was a master of acknowledging tradition before examining it critically in the light of his empirical method. His method can be a great inspiration for us when we try to manage the pervasive tensions between tradition and innovation.