LEARNING FROM
LEONARDO

Decoding the Notebooks of a Genius

Learning from Leonardo

Berrett-Koehler Publishers, Inc.
235 Montgomery Street, Suite 650
San Francisco, California 94104-2916
Tel: (415) 288-0260, Fax: (415) 362-2512
www.bkconnection.com

Ordering information for print editions
Quantity sales. Special discounts are available on quantity purchases by corporations,
associations, and others. For details, contact the "Special Sales Department" at the
Berrett-Koehler address above.
Individual sales. Berrett-Koehler publications are available through most bookstores. They
can also be ordered directly from Berrett-Koehler: Tel: (800) 929-2929; Fax: (802) 864-7626;
www.bkconnection.com
Orders for college textbook/course adoption use. Please contact Berrett-Koehler:
Tel: (800) 929-2929; Fax: (802) 864-7626.
Orders by U.S. trade bookstores and wholesalers. Please contact Ingram Publisher
Services, Tel: (800) 509-4887; Fax: (800) 838-1149; E-mail: customer.service@ingrampublisherservices.com; or visit

www.ingrampublisherservices.com/Ordering for details
about electronic ordering.

Berrett-Koehler and the BK logo are registered trademarks of
Berrett-Koehler Publishers, Inc.

First Edition
Hardcover print edition ISBN 978-1-60994-989-1
PDF e-book ISBN 978-1-60994-990-7
IDPF e-book ISBN 978-1-60994-991-4

2013-1

Produced by Wilsted & Taylor Publishing Services.

Copyediting: Nancy Evans. Design: Yvonne Tsang. Index:
Andrew Joron.

Jacket images: Wing © Horacio Villalobos/epa/Corbis; Ms. B,
folio 88v (detail).

Endsheets: Codex Leicester, folios 35v and 2r (detail).

Frontispiece: Profile of an old man (detail). Windsor Collection,
Landscapes, Plants, and
Water Studies, folio 48r.

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).

CONTENTS

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.

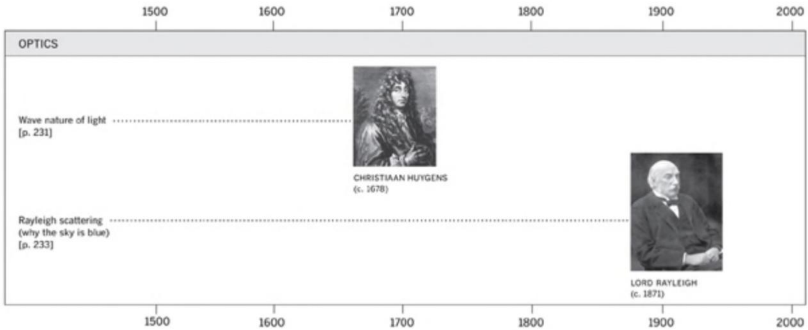
From their correspondence it is evident that Galileo, Newton, and their contemporaries struggled with many of the same problems that Leonardo had recognized and often solved one or two centuries earlier. Moreover, they used similar metaphors and reasoned in similar ways, so they would have understood 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.

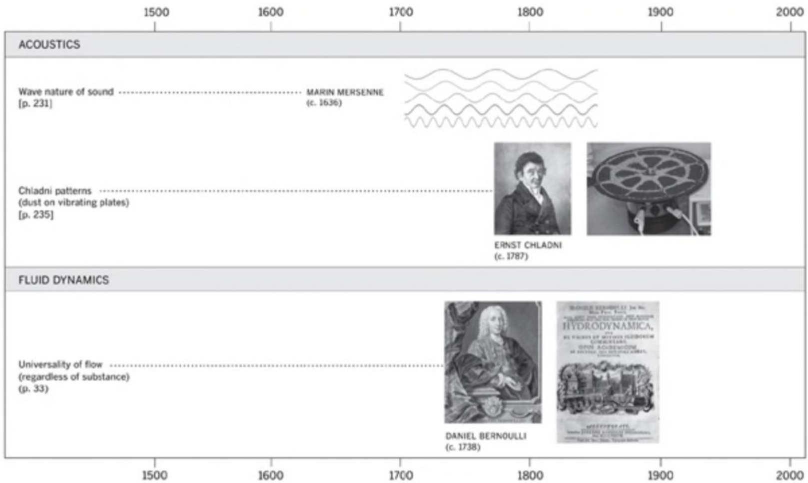
Fritjof Capra
Berkeley
February 2013

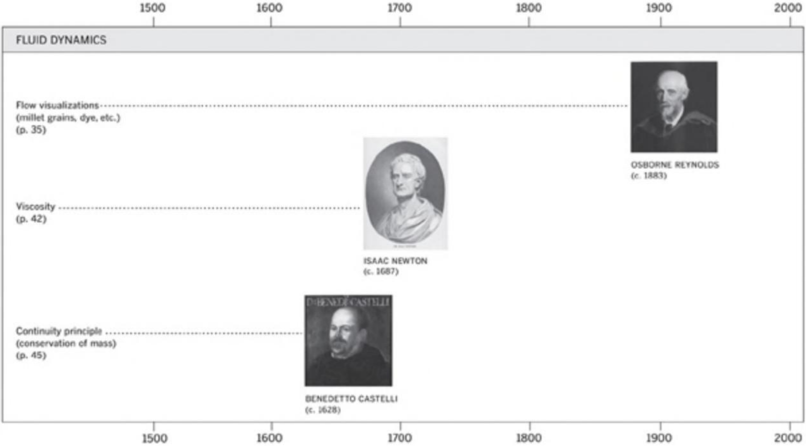
TIMELINE OF SCIENTIFIC DISCOVERIES

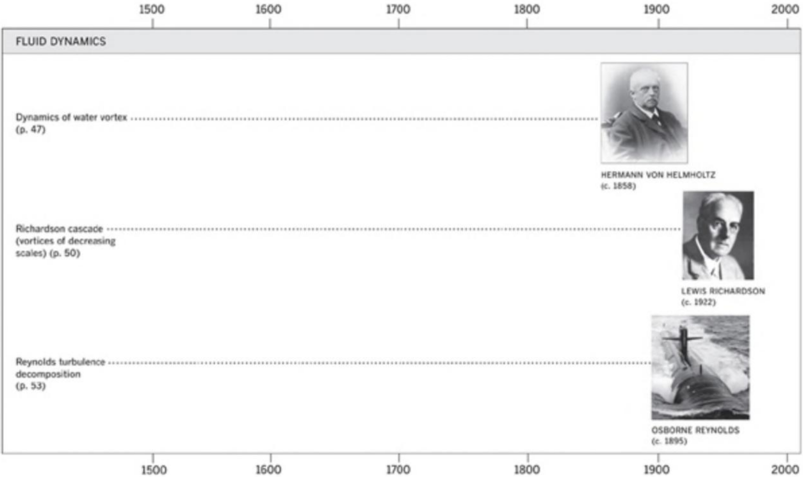
The following chart lists the most important scientific discoveries made by Leonardo da Vinci during the fifteenth and sixteenth centuries, together with the approximate dates when they were rediscovered by other scientists. It also includes references to the pages of this book (in parentheses) where 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
FLUID DYNAMICS
Flow visualizations (millet grains, dye, etc.) (p. 35)
OSBORNE REYNOLDS (c. 1883)
Viscosity (p. 42)
ISAAC NEWTON (c. 1687)
D. BENED. CASTELLI
Continuity principle (conservation of mass) (p. 45)
BENEDETTO CASTELLI (c. 1628)


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)

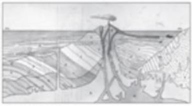
1500 1600 1700 1800 1900 2000

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

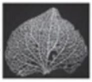
1500 1600 1700 1800 1900 2000

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

1500 1600 1700 1800 1900 2000

BOTANY

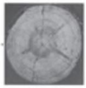
Tropism (orientation of plants in response to stimuli) (p. 120)

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

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

1500 1600 1700 1800 1900 2000

MECHANICS

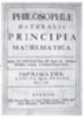
Anticipation of "arrow of time" (irreversible processes) (p. 188)

ARTHUR EDDINGTON (c. 1928)

Parabolic nature of ballistic trajectories (p. 196)

GALILEO GALILEI (c. 1609)

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



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA

ISAAC NEWTON (c. 1687)

1500 1600 1700 1800 1900 2000

1500 1600 1700 1800 1900 2000

AERODYNAMICS

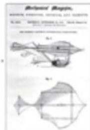
Aerodynamics: the proper basis for a science of flight (p. 265)

GEORGE CAYLEY (c. 1809)

Principle of the wind tunnel (p. 266)

FRANCIS WENHAM (c. 1871)

Density distribution around a bird wing (p. 267)



GEORGE CAYLEY (c. 1810)

1500 1600 1700 1800 1900 2000

1500 1600 1700 1800 1900 2000

HUMAN ANATOMY

Sphincter of the pupil [p. 240]

FREDERIK RUYSCH (c. 1691)

Atria of the heart (p. 291)

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)

Discovery of aortic sinuses (sinuses of Valsalva) (p. 300)

ANTONIO VALSALVA (c. 1710)

1500 1600 1700 1800 1900 2000

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)

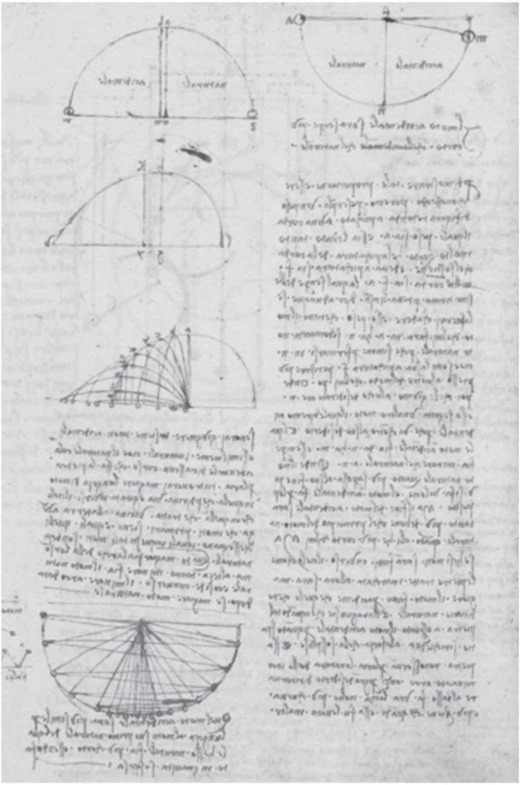
HUMBERTO MATURANA (c. 1970)

ECOLOGY

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

CHARLES ELTON (c. 1927)

1500 1600 1700 1800 1900 2000



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 establish 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.

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

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.

For most of us, intellectual fearlessness can mean learning how to trust our intuition and creativity, which may lead to novel ideas or solutions. If we have the courage to explore these new ideas without fear of rejection or ridicule, we will often be highly rewarded.

The spontaneous emergence of novelty in social networks, often referred to simply as “emergence,” has been recognized as a key characteristic of life. Complexity theory has revealed the underlying dynamics of emergence: a network of communications involving multiple feedback loops, open to disturbances from the environment; then a critical point of instability; and finally a breakthrough to a new order, or new idea.[13] Trusting our collective intuition and creativity creates an environment conducive to that emergence of novelty.

This is the basis of a new understanding of leadership that is now being explored by organizational theorists and business executives.[14] The traditional idea of a leader is that of a person who is able to hold a vision, to articulate it clearly, and to communicate it with passion and charisma. This is still important, but another kind of leadership facilitates the emergence of novelty by creating conditions rather than giving directions and by using the power of authority to empower others.

Leaders need to recognize and understand the different stages of this fundamental life process. Emergence requires an active network of communications. Moreover, the emergence of novelty is a property of open systems, which means that the organization needs to be open to new ideas and new knowledge. Facilitating emergence, therefore, means first of all building up and nurturing networks of communications and then creating openness—a learning culture in which continual questioning is encouraged and innovation is rewarded. In the end, leaders need to be able to recognize the emergent novelty, articulate it, and incorporate it into the organization's design. Not all emergent solutions will be viable, however, and hence a culture that fosters emergence must include the freedom to make mistakes. In such a culture, experimentation is encouraged and learning from failures is valued as much as success. Leonardo da Vinci's relentless curiosity and intellectual fearlessness can thus be highly inspiring to a new generation of business and community leaders.

When we look at the state of the world today, it is clear that the major problems of our time—energy, the environment, climate change, food security, and financial security—cannot be understood in isolation. They are systemic problems, which means that they are all interconnected and interdependent; they require systemic thinking to be solved. We need to learn how to take into account the interdependence of our problems, and we often need to work on several of them simultaneously to solve any one of them.

This was exactly Leonardo's method, and this—together with his deep respect for nature—is perhaps his greatest legacy to us. I shall return to this legacy in the Coda of this book; but first let us explore Leonardo da Vinci's marvelous world of living forms and transformations.

PART I
Form and Transformation in the Macrocosm

1
The Movements of Water

Among the four classical elements, water held by far the greatest fascination for Leonardo. Throughout his life, he studied its movements and flows, drew and analyzed its waves and vortices, and speculated about its role as the fundamental "vehicle of nature" (*vetturale della natura*) in the macrocosm of the living Earth and the microcosm of the human body.[1]

Leonardo's notes and drawings about his observations and ideas on the movement of water fill several hundred pages in his Notebooks. They include elaborate conceptual schemes and portions of treatises in the

Codex Leicester and in Manuscripts F and H, as well as countless drawings and notes scattered throughout the Codex Atlanticus, the Codex Arundel, the Windsor Collection, the Codices Madrid, and Manuscripts A, E, G, I, K, and L.[2] The sheer bulk of Leonardo's writings on water duly impressed his contemporaries and succeeding generations of historians. In fact, water was the only subject, apart from painting, of which an extensive compilation of handwritten transcriptions from the Notebooks was made. This collection of notes, transcribed in the seventeenth century and comprising 230 folios, was published in 1828 in Bologna under the title *Della natura, peso, e moto dell'acque* (On the Nature, Weight, and Movement of Water).[3]

Carrier and Matrix of Life

Leonardo was fascinated by the nature and movements of water for several reasons. I believe that, ultimately, they all have to do with his persistent quest to understand the nature of life, which informed both his science and his art. Leonardo's science is a science of living, organic forms, and he clearly recognized that all organic forms are sustained and nourished by water:

PRECEDING A stream running through a rocky ravine, c. 1483 (detail, see fig. 2-5).
FACING "Water falling upon water," c. 1508–9 (see fig. 1-13).

> It is the expansion and humor of all living bodies.
> Without it nothing retains its original form.[4]

The term "humor" is used here in its medieval sense of a nourishing bodily fluid. In another Notebook, Leonardo wrote: "[Water] moves the humors of all kinds of living bodies."[5] Being a painter, he had ample experience with water as a solvent and accurately described this chemical property: "It has nothing of itself, but moves and takes everything, as is clearly shown when distilled."[6]

Leonardo's view of the essential role of water in biological life is fully borne out by modern science. Today we know not only that all living organisms need water for transporting nutrients to their tissues but also that life on Earth began in water. The first living cells originated in the primeval oceans more than three billion years ago, and ever since that time all the cells that compose living organisms have continued to flourish and evolve in watery environments. Leonardo was completely correct in viewing water as the carrier and matrix of life.

One of the fundamental principles of Leonardo's science is the similarity of patterns and processes in the macro- and microcosm. Accordingly, he compared the "water veins" of the Earth to the blood vessels of the human body (see p. 26).[7] As blood nourishes the tissues of the body, so water nourishes the Earth's vegetation with its "life-giving moisture."[8] And as water expands when it vaporizes in the heat of the sun and "becomes mingled with the air," so blood by its warmth spreads into the periphery of the body.[9] Indeed, we shall see that Leonardo described in great detail how blood carries nutrients to the bodily tissues and that he developed an ingenious, though incorrect, theory of how body heat is generated by the turbulent flows of blood in the chambers of the heart (see p. 296).

In his paintings, Leonardo represented water as the carrier of life not only in the scientific sense but also symbolically, in the religious sense. According to the Christian theology that shaped the culture in which he lived, the faithful receive a new spiritual life in the sacrament of baptism, and water is the medium that conveys this sacrament. In the words of the Bible, baptism is rebirth of water and spirit (John 3:5). Several of Leonardo's paintings contain variations on this fundamental religious theme, often integrating the religious symbolism with his scientific understanding of the life-giving quality of water.

This integration is already apparent in the very first record we have of Leonardo as a painter, when he was still an apprentice in the workshop of Andrea del Verrocchio in Florence. Around 1473, when Leonardo was twenty-one, Verrocchio let the youth paint one of two angels and parts of the background in his picture of the *Baptism of Christ* (plate 2).[10] Leonardo painted a wide, romantic stretch of hills and pinnacles of rocks of the kind that would form the backgrounds in many of his later paintings, and to that he added a long watercourse, flowing from a pool in the far distance all the way to the foreground, where it forms small waves rippling around the legs of Christ. While these ripples in the foreground represent the lifegiving water of the sacrament, the watercourse in the background, cutting through arid rocks and flowing into a fertile valley, portrays water as the carrier of biological life in the macrocosm of the Earth.

This theme is expanded and elaborated in several of Leonardo's later paintings, in particular, in three of his masterpieces—the *Virgin of the Rocks* (plate 8), the *Mona Lisa* (plate 11), and the *Madonna and Child with Saint Anne* (plate 7). In the *Virgin of the Rocks*, Leonardo depicts a prophetic meeting of the infant Christ with the infant Saint John long before the Baptism. According to a fourteenth-century legend, this meeting took place during the Holy Family's flight into Egypt, where they lived in the wilderness after their escape from Herod's massacre of the innocents. Leonardo has placed the scene in front of a rocky grotto and turned it into a complex 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.[11] An angel conspicuously points to the Baptist, directing our attention to his spiritual dialogue with Christ, while Mary tenderly protects the children with her outstretched arms.

As in Verrocchio's *Baptism*, a mountain stream emerges in the far distance from the misty atmosphere surrounding pinnacles of rocks and breaks through the rocky landscape, flowing all the way to the foreground of the painting where it runs through a small pool—an allusion to the Baptism. However, the rocks are rendered here in much more detail and with astonishing geological accuracy (see pp. 77ff.), and the luxuriant vegetation in the grotto's moist environment is clear testimony to the generative powers of water, presented by the artist in a subtle synthesis of scientific knowledge and religious symbolism (see pp. 102ff.).

The *Mona Lisa* is Leonardo's deepest meditation on the mystery of the origin of life—the theme that was foremost in his mind during his old age. The central theme of the artist's most famous painting is life's procreative power, both in the female body and in the body of the living Earth. Essential to this power is the fundamental role of water as the life-giving element (see pp. 318ff.).

The theme of the origin of life is taken up again in the *Saint Anne*, which Leonardo painted around the same time as the *Mona Lisa*. Here the artist returned once more to exploring the mystery of life within a religious context. The painting shows Mary, her mother Saint Anne, and the Christ child together with a lamb in a highly original composition. Its theological message can be viewed as a continuation of Leonardo's long meditation on the destiny of Christ, which began with the *Virgin of the Rocks*.[12]

Once more, the familiar mountain lakes and jagged rocks rise high into the background, although they are less imposing than those behind the *Mona Lisa*. In both paintings, the central theme is the mystery of the origin of life in the human body and in the body of the Earth. In the *Saint Anne*, this is rendered even more complex by the presence of three generations and by the myth of the virgin birth. There is a double mystery here: the immaculate conception of Mary by Saint Anne and that of Christ by Mary. To emphasize the analogy between human nature and the Earth, Leonardo has mirrored the three generations in the painting's foreground by three tiers of mountain lakes, interlinked by small waterfalls, in the background.

What these four paintings—the *Baptism*, the *Virgin of the Rocks*, the *Mona Lisa*, and the *Saint Anne*—have in common is Leonardo's extended reflection on water as the life-giving element in the macrocosm of the Earth and the microcosm of human existence. Drawing on his scientific understanding, his artistic genius, and his great familiarity with religious symbolism, Leonardo expressed this meditation in a series of masterpieces that have become enduring icons of European art.

Nature's Fluid Forms

Another reason Leonardo was so fascinated by water is that he associated it with the fluid and dynamic nature of organic forms. Ever since antiquity, philosophers and scientists had recognized that biological form is more than shape, more than a static configuration of components in a whole. There is a continual flux of matter through a living organism, while its form is maintained; there is growth and decay, regeneration and development. This dynamic conception of living nature is one of the main themes in Leonardo's science and art.[13] He portrayed nature's forms—in mountains, rivers, plants, and the human body—in ceaseless movement and transformation. And, knowing that all organic forms are sustained by water, he sensed a deep connection between their fluidity and the fluidity of water.

As Leonardo observed the flow of the life-giving element, he marveled at its endless versatility and adaptability. "Running water has within itself an infinite number of movements," he noted in Manuscript G, "sometimes swift, sometimes slow, and sometimes turning to the right and sometimes to the left, now upwards and now downwards, turning over and back on itself, now in one direction and now in another, obeying all the forces that move it."[14] In the Codex Atlanticus he wrote: "Thus, joined to itself, water turns in a continual revolution. Rushing this and that way, up and down, it never rests, neither in its course nor in its nature. It owns nothing but seizes everything, taking on as many different characters as the places it crosses."[15]

In addition, Leonardo carefully studied the actions of water in the erosion of rocks and river banks, its transformations into solid and gaseous forms (known in science today as phase transitions), and its properties as a chemical solvent. He never divided these diverse properties into separate categories but saw them all as different aspects of the fundamental role of water in nourishing and sustaining life:

> Without any rest, it is ever removing and consuming whatever borders upon it. So at times it is turbulent and goes raging in fury, at times clear and tranquil it meanders playfully with gentle course among the fresh pastures. At times it falls from the sky in rain, snow, or hail. At times it forms great clouds out of fine mist. At times it moves of itself, at times by the force of others. At times it increases the things that are born with its life-giving moisture. At times it shows itself either fetid or full of pleasant odors. Without it nothing can exist among us.[16]

For Leonardo, the fluid and ever-changing forms of water were extreme manifestations of the fluidity that he saw as a fundamental characteristic of all the forms of nature. He also noticed, however, that certain flows of water can produce forms that are surprisingly stable: eddies, vortices, and other forms of turbulence known to scientists today as coherent structures (see p. 55). He observed and sketched a great variety of these relatively stable turbulent structures, and I believe that his lifelong fascination with them came from his deep intuition that, somehow, they embodied an essential characteristic of living, organic forms.

Today, from our modern perspective of complexity theory and the theory of living systems, we can say that Leonardo's intuition was absolutely correct. The fundamental characteristic of a water vortex—for example, the whirlpool that is formed as water drains from a bathtub—is that it combines stability and change. The vortex has water continuously flowing through it, and yet its characteristic shape, the well-known spirals and narrowing funnel, remains remarkably stable. This coexistence of stability and change is also characteristic of all living systems, as complexity and systems theorists recognized in the twentieth century.[17]

The process of metabolism, the hallmark of biological life, involves a continual flow of energy and matter through a living organism—the intake and digestion of nutrients and the excretion of waste products—while its form is maintained. Thus, metaphorically, one could visualize a living organism as a whirlpool, even though the metabolic processes at work are not mechanical but chemical.

Leonardo never used the analogy between the dynamic of a water vortex and that of biological metabolism, at least not in the Notebooks that have come down to us. However, he was well aware of the nature of metabolic processes. Indeed, we shall see that his detailed description of tissue metabolism in connection with the flow of blood in the human body must be seen as one of his most astonishing scientific insights (see p. 312). Thus, it seems not too far-fetched to assume that he was so fascinated by whirlpools and vortices because he intuitively recognized them as symbols of life—stable and yet continually changing.

A Source of Power

Leonardo saw water not only as the life-giving element but also as the principal force shaping the Earth's surface and as a major source of power, which could be harnessed by human ingenuity. In his time, three hundred years before the Industrial Revolution, the windmill, the water wheel, and the muscles of beasts provided the only power to drive human technologies, and among those Leonardo thought that water had the greatest potential. At the age of fifty, when he was famous as a painter throughout Europe and known as one of Italy's leading military and hydraulic engineers, he dreamed of a grand scheme for a kind of “industrial” canal along the river Arno between Florence and Pisa.[18] He imagined that such a waterway would provide irrigation for the surrounding fields as well as energy for numerous mills that could produce silk and paper, drive potters’ wheels, saw wood, forge iron, burnish arms, and sharpen metal.[19] Leonardo’s ambitious project was never realized, but it was a prophetic vision. Centuries later, the powers of steam and hydroelectricity would indeed transform human civilization.

As an engineer, Leonardo was also well aware of the destructive power of water. In the plains of northern Italy, at the foot of the Alps, an elaborate system of canals had been built for irrigation and for commercial navigation, and one of the main challenges faced by hydraulic engineers was how to protect these canals from the flooding of their tributaries (see p. 32). This flooding happened periodically during heavy autumn rains and after a sudden spring melting of the Alpine snows. Leonardo paid great attention to these inundations, which could be very violent. He had witnessed a catastrophic flooding of the Arno in his native Tuscany at the age of fourteen. This childhood experience must have left a deep impression on him and perhaps was the cause of his morbid fascination with floods, which he considered the most frightening of all cataclysmic events.[20] “How can I find words to describe these abominable and frightening evils, against which there is no human defense?” he wrote in the Codex Atlanticus. “With swollen waves rising up, it devastates high mountains, destroys the strongest embankments, and tears out deeply rooted trees. And with voracious waves, laden with the mud of plowed fields, it carries off the fruits of the hard work of the miserable and tired tillers of the soil, leaving the valleys bare and naked with the poverty it leaves in its wake.”[21]

As a hydraulic engineer, Leonardo invented special machines for digging canals, improved the existing systems of locks, drained marshes, and modified the flows of rivers to prevent damage to properties along their banks. As an architect, he designed elaborate landscape gardens with splendid fountains, running water for cooling wine, sprinkler systems for refreshing guests during the hot summers, and automatic musical instruments played by water mills.[22]

He decided early on that his reputation and skills in hydraulic engineering and landscape design would be grounded in a thorough understanding of the flow of water. In his science and his art, Leonardo never tired of observing, analyzing, drawing, painting, and studying how water moves through the air, the blood vessels of the human body, the vascular tissues of plants, and the seas and rivers of the living Earth.

The Water Cycle

Since Leonardo’s science was based on repeated observations of natural phenomena combined with meticulous analysis,[23] it is not surprising that he had an accurate understanding of the evaporation and condensation of water and was able to describe it clearly. “Readily it rises up as vapors and mists,” he wrote in Manuscript A, “and, converted into clouds, it falls back as rain because the minute parts of the cloud fasten together and form drops.”[24] A slightly more detailed description can be found in the Codex Arundel:

> At times it is bathed in the hot element and, dissolving into vapor, becomes mingled with the air; and drawn upward by the heat, it rises until, having found the cold region, it is pressed closer together by its contrary nature, and the minute particles become attached together.[25]

He was also well aware of the fact that water continually cycles through the earth and atmosphere: “We may conclude that the water goes from the rivers to the sea, and from the sea to the rivers, thus constantly circulating and returning.”[26] Taken together, these statements seem to indicate that Leonardo had a clear understanding of the essential phases of the water cycle—how water in the oceans, heated by the sun, evaporates into the air; how it rises into the atmosphere until cooler temperatures cause it to condense into clouds; how minute particles in the clouds coalesce into larger drops that precipitate as rain or snow; and how this precipitation eventually flows into rivers that carry it back into the oceans.

In actual fact, however, Leonardo’s views of the water cycle were far from clear. He considered several different explanations, struggled for many years because none of them satisfied his critical mind, and arrived at the correct view only in his old age, in his early sixties. How are we to understand that? What prevented a man of his genius from understanding a natural process that seems so evident to us today?

The answer to the puzzle provides a fascinating example of the tremendous power of the philosophical framework known today as a scientific paradigm—the constellation of concepts, values, and perceptions that form the intellectual context of all scientific investigations.[27] One of the foundations of the medieval worldview was the conviction that nature as a whole was alive, and that the patterns and processes in the macrocosm were similar to those in the microcosm. This analogy between macro- and microcosm, and in particular between the Earth and the human body, goes back to Plato and had the authority of common knowledge in the Middle Ages and the Renaissance.[28] Leonardo fully embraced it as one of the guiding principles of his science and discussed it repeatedly (see pp. 65ff.). Whenever he explored the forms of nature in the macrocosm, he also looked for similarities of patterns and processes in the human body, and so it was natural for him to compare the "water veins" of the Earth to the blood vessels of the body.

Our modern systemic conception of life fully validates Leonardo's method of exploring similarities between patterns and processes in different living systems, and his view of the Earth as being alive has reappeared in today's science, where it is known as Gaia theory.[29] However, Leonardo ran into difficulties with his comparisons between the living Earth and the living human body because he extended them beyond the similarity of patterns to comparisons of forces and material structures. One of the important insights of modern systems and complexity theories has been that, even though patterns of relationships between the components and processes of two different living systems may be similar, the processes themselves and the forces and structures involved in them may be quite different.[30] It took Leonardo the better part of his life to realize this, but he clearly did so in his old age.

Since the total amount of water on Earth is finite, Leonardo argued, the water carried into the sea by the rivers must somehow cycle back to their sources, "thus constantly circulating and returning."[31] Since he conceived of water as a "humor" that nourishes the Earth just as the blood nourishes the human body, he imagined that there must be water veins inside the body of the living Earth corresponding to the blood vessels in the bodies of animals and humans:

> The body of the Earth, like the bodies of animals, is interwoven with a network of veins which are all joined together, and are formed for the nutrition and vivification of that Earth and of its creatures. They originate in the depths of the sea, and there after many revolutions they have to return through the rivers, created high up by the bursting of these veins.[32]

This was the traditional view, put forward by philosophers from Aristotle to the Renaissance: inside the living Earth, there is a system of water veins, in which the water circulates like the blood in a living body, until the veins eventually break in the high mountains. There, the water emerges from mountain springs, is collected by the rivers, and flows back into the sea. Leonardo realized, of course, that rivers are also fed by rainwater and melting snow. But for many years he maintained that their principal sources were the internal veins of the Earth. Even though he encountered many logical inconsistencies, he was unwilling for the longest time to abandon the powerful analogy between the circulation of water in the Earth and that of blood in the human body. "The water that rises within the mountains," he wrote in his early forties, "is the blood that keeps these mountains alive."[33]

Leonardo's scientific mind was not content with the beautiful metaphorical description of water as "the blood that keeps the mountains alive." He needed to explain how the water actually rises up to the mountain springs through internal channels. It was clear to him that some forces counteracting gravity had to be at work:

> The water which sees the air through the broken veins of the high mountain summits is suddenly abandoned by the power which brought it there, and when it escapes from these forces that elevated it to the summit, it freely resumes its natural course.[34]

But what exactly were these forces? To find an answer, Leonardo used a method that was characteristic of all his investigations. Understanding a phenomenon, for him, always meant connecting it with other phenomena through a similarity of patterns. In this case, he identified two similar phenomena—how the blood in the human body rises to the head and how the sap in a plant rises up from its roots—and he assumed that the same forces were acting in all three examples:

> The same cause which moves the humors in all kinds of living bodies against the natural course of gravity also propels the water through the veins of the Earth, wherein it is enclosed, and distributes it through small passages. As the blood rises from below and pours out through the broken veins of the forehead, and as the water rises from the lower part of the vine to the branches that are cut, so from the lowest depth of the sea the water rises to the summits of the mountains where, finding the veins broken, it pours down and returns to the low-lying sea.[35]

Having established this similarity of patterns, Leonardo then set out to identify the common forces underlying them. Over the years, he tried and then rejected several explanations.[36] At first, he thought that the water was drawn up inside the mountains as steam by the heat of the sun, and he suggested that this process was similar to blood rising to a man's head when it is hot:

> When the sun warms a man's head, the blood increases and rises so much with other humors that, by pressuring the veins, it often causes headaches.[37]

"The heat of fire and sun by day," Leonardo argued, "have the power to extract the moisture from the low places of the mountains and draw it up high in the same way as it draws the clouds and extracts their moisture from the bed of the sea."[38]

Subsequently, however, he discovered two reasons why this explanation could not work. He noted that on the highest mountain tops, closest to the heating sun, the water remains cold and is often icy. Moreover, with this mechanism the greatest amount of water should be drawn up in summer when the sun is hottest, but mountain rivers are often lowest at this time.

In a second explanation, Leonardo suggested that the water might be drawn up in a process of distillation, fueled by the Earth's internal heat. He was aware of the presence of fire within the Earth from observations of hot springs and volcanoes, and he had also experimented with several types of distillation apparatus.[39] Perhaps, he suggested, the interior fires of the Earth boil water in special caverns until it rises as vapor to the roofs of those caverns, "where, coming upon the cold, it suddenly changes back into water, as one sees happen in a retort, and goes falling down again and forming the beginnings of rivers."[40] Again, Leonardo found an argument against his own explanation. Such extensive distillation, he realized, would keep the roofs of internal caverns wet from the rising steam, but he remembered from his explorations of mountain caves that they were often bone dry.

A third proposal was based on the observation that water rises in a vacuum within an enclosed space. Leonardo was quite familiar with this phenomenon. One of his early inventions, when he was still working in Verrocchio's *bottega*, had been a method of creating a vacuum to raise water by means of a fire burning in a closed bucket.[41] Now he hypothesized that the internal fires might rarefy the air in the Earth's caverns and thus raise the water to the top. However, he soon realized that this would not work, because additional air would enter the cavern through the openings of the mountain springs and would thus stop the siphoning action of the vacuum.

On a folio of the Codex Leicester, Leonardo summarized both the distillation model and the siphoning model together with their counterarguments.[42] He illustrated the discussion with a drawing showing the cross section of a mountain with interior veins running from the sea all the way up to the top where they connect with two large caverns. Right below, we see clear sketches of the two processes of distillation and siphoning (fig. 1-1). An accompanying folio contains numerous drawings illustrating experiments with various siphons.[43]

As yet another alternative, Leonardo suggested that the water might be drawn up inside the mountains by some process similar to the action of a sponge, but that vague idea did not satisfy him either. "If you should say that the Earth's action is like that of a sponge," he countered, "the answer is that, even if the water rises to the top of that sponge by itself, it cannot then pour down any part of itself from this top, unless it is squeezed by something else, whereas with the summits of the mountains one sees the opposite, for there the water always flows away by itself without being squeezed by anything."[44]

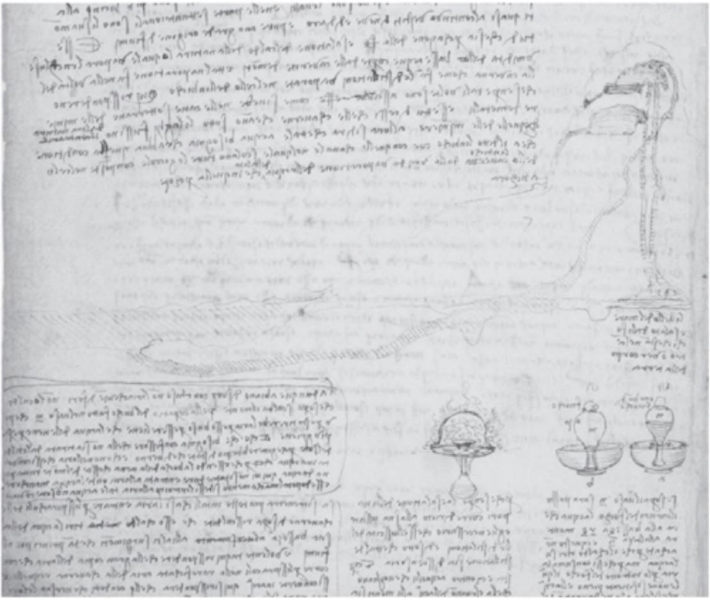


FIG. 1-1. Models of water circulation by distillation and by siphoning action. Codex Leicester, folio 3v (detail).

After many years of considering various explanations and finding counterarguments to all of them, Leonardo finally realized that his analogy between the blood vessels of the human body and the water veins of the Earth was too narrow; that in the water cycle, the water does not circulate inside the mountains but rises as vapor through the air, drawn up by the heat of the sun, and then falls as rain on the mountaintops. On a folio of the Windsor Collection, written after 1510 when he was around sixty, Leonardo stated unequivocally that "the origin of the sea is contrary to the origin of the blood," because the rivers "are caused entirely by the aqueous vapors raised up into the air."[45]

Around the same time, in a note in Manuscript G about water as the carrier of minerals, Leonardo stated quite casually, as a matter of fact, that the rivers are produced by clouds:

> The saltiness of the sea is due to the numerous water veins, which in penetrating the earth find the salt mines, and dissolving parts of these carry them away with them to the ocean and to the other seas from whence the clouds, originators of the rivers,* never raise them up.[46]

From our contemporary perspective, Leonardo's long intellectual struggle to understand the water cycle is extremely interesting. His successive theoretical formulations are quite similar to the theoretical models that are characteristic of modern science.[47] Like scientists today, he continually tested his models and was ready to replace them when he found that they contradicted some empirical evidence. Moreover, as he progressed, he kept in mind the analogies and interconnecting patterns to phenomena in other areas, and revised his theories about those other phenomena accordingly. Thus, as he modified his explanations of the water cycle, he also modified similar models of the functioning of the heart and the flow of blood in the human body (see pp. 284–85).

In the end, Leonardo came to realize that, although water and blood both carry nutrients to living systems (as we would say today) and both cycle continually, the pathways of the two cycles and the forces driving them are quite different. During the years of 1510–15, when he finally reached a clear understanding of the water cycle, he also came to the conclusion that the blood in the human body is moved by the pumping action of the heart (see pp. 290ff.). That Leonardo was able, in his old age, to abandon the narrow analogy between the circulation of blood in the human body and the circulation of water in the body of the Earth, which had been firmly established in medieval philosophical thought, is an impressive testimony to his intellectual integrity, his perseverance, and the power of his scientific method.

When he was in his early sixties and reached his full understanding of the water cycle and the movement of blood in the human body, Leonardo also produced his most sophisticated writings in botany, in which he described the transport of "vital sap" through the vascular tissues of plants (see pp. 120ff.). It would be fascinating to know how his insights into the circulation of water and blood affected his ideas of how water rises through the plant tissues from the roots to the top. Today we know that this is a consequence of the evaporation of water from the leaves and of its intermolecular forces—the "cohesion in itself," as Leonardo called it (see p. 41). Unfortunately, we are not likely to ever know Leonardo's last thoughts on these matters since the manuscript that may have contained his definitive treatise on botany has been lost.[48]

From Hydraulic Engineering to the Scientific Study of Flow

The majority of Leonardo's extensive collections of notes and drawings on the flow of water were concerned with problems of hydraulic engineering and with the phenomenon of flow itself. In the Renaissance, the latter was a subject unique to Leonardo. The movement of rigid bodies had been studied since antiquity. In contrast, although hydraulic engineers had produced magnificent works—from the great aqueducts and luxurious thermal baths of the Romans to the ingenious navigation locks of the early fifteenth century—it had not occurred to any of them to wonder how flowing water could be described mathematically. Nor did they attempt to explore the fundamental laws of fluid flow, the subject of our modern discipline of fluid dynamics. Leonardo did both. His investigations, drawings, and attempted mathematical descriptions of flow patterns in water and air must be ranked among his most original scientific contributions, leading him to discoveries that would reappear only centuries later.

When he was first employed as painter and "ducal engineer" at the Sforza court in Milan in 1490, Leonardo had already spent eight years in the capital of Lombardy, which was a vibrant trading center of tremendous wealth and a major seat of political power in northern Italy. During those years, he had not only painted the *Virgin of the Rocks* and a highly original portrait of the mistress of Ludovico Sforza, but had also undertaken an extensive program of self-education during which he systematically studied the principal fields of knowledge of the time.[49]

From his first years in Lombardy, Leonardo was fascinated by the engineering problems involved in the region's elaborate system of canals. During the previous three centuries, hydraulic engineering in northern Italy had reached a level of considerable sophistication.[50] The wealth of the Lombard region was dependent on the control of water and on land reclamation from marshes. Hydraulic engineering was needed to reduce damage from the periodic flooding of Alpine rivers, to supply the cities with water, to keep ports working, for irrigation, and for commercial navigation. The great canals of Lombardy, wide enough to let two large barges pass, interconnected the principal rivers of the area and featured a series of sophisticated locks for overcoming differences of water levels.

As ducal engineer at the Sforza court, Leonardo was probably in charge of all hydraulic works and thus became thoroughly familiar with the existing technologies and the problems that needed to be solved.[51] Indeed, the Codex Leicester contains a vast number of observations on practical hydraulic problems in rivers and canals. Before Leonardo, such knowledge had been transmitted mostly orally, and the approach of the Lombard engineers was purely empirical: all their practices and rules were based on the success or failure of previous similar works. This did not satisfy Leonardo's scientific mind. He needed to know the reasons behind the empirical rules, and so he embarked on his lifelong studies of the laws of fluid flow, beginning with the basic dynamics of the flow of rivers and proceeding to complex patterns of turbulent flow.

Even in the midst of his theoretical studies, Leonardo always kept their practical applications in mind. For example, during a discussion of the flow of water around immersed obstacles, he noted: "The science of these objects is of great usefulness, for it teaches how to bend rivers and avoid the ruins of the places struck by them."[52] In Manuscript F, written during the same period as the Codex Leicester, we find the following admonition: "When you put together the science of the movements of water, remember to put beneath each proposition its applications, so that such science may not be without its uses."[53]

In Leonardo's time, the scientific study of flow phenomena, now known as fluid dynamics, was entirely new. It was a field of study he himself created single-handedly. However, in view of his dynamic conception of the world and his practice of portraying nature's forms in his drawings and paintings as being in ceaseless movement and transformation, such a study must have seemed completely natural to him. Indeed, flow was one of the dominant themes in his science and art. In the words of hydraulic engineer and Leonardo scholar Enzo Macagno, "To Leonardo, if not everything, almost everything was flowing or could be in one state of flow or another."[54]

In early Greek philosophy, the idea that everything in the world is in a process of constant change was expressed in the famous saying by Heraclitus of Ephesus, "Everything flows." There is no evidence that Leonardo was familiar with the philosophy of Heraclitus, but in an intriguing double portrait by the famous architect Donato Bramante, who was a close friend of Leonardo, Bramante represented his friend as Heraclitus and himself as Democritus.[55]

Since he saw movement and transformation as fundamental characteristics of all natural forms, Leonardo assumed that the basic properties of flow were the same for all fluids, and he found this confirmed by his observations. He emphasized especially the similarity between flows of water and air. "In all cases of motion, there is great conformity between water and air," he noted in Manuscript A,[56] and in the Codex Atlanticus: "The movement of water within water acts like that of air within air."[57] However, Leonardo was well aware that air differs from water in being "infinitely compressible,"* whereas water is incompressible.[58]

As far as flows of liquids were concerned, Leonardo experimented not only with water but also investigated the flows of blood, wine, oil, and even those of grains like sand and seeds.[59] His experiments with granular materials are especially remarkable. He realized that he could learn something about the flow of water by observing a similar but somewhat simpler phenomenon—the flow of grains in which the individual flowing particles are actually visible. This method of using simplified models to analyze the essential features of complex phenomena is an outstanding characteristic of our modern scientific method.[60] The fact that Leonardo used it repeatedly is truly remarkable. In his view of flow as a universal phenomenon of gases, liquids, and