Fritjof Capra and Pier Luigi Luisi

The Systems View of Life

A Unifying Vision

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Over the past 30 years, a new systemic conception of life has emerged at the forefront of science. New emphasis has been given to complexity, networks, and patterns of organization, leading to a novel kind of "systemic" thinking.

This volume integrates the ideas, models, and theories underlying the systems view of life into a single coherent framework. Taking a broad sweep through history and across scientific disciplines, the authors examine the appearance of key concepts such as autopoiesis, dissipative structures, social networks, and a systemic understanding of evolution. The implications of the systems view of life for healthcare, management, and our global ecological and economic crises are also discussed.

Written primarily for undergraduates, it is also essential reading for graduate students and researchers interested in understanding the new systemic conception of life and its implications for a broad range of professions – from economics and politics to medicine, psychology, and law.

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To the memory of
Francisco Varela (1946–2001),
who introduced us to each other and who inspired both of us
with his systemic vision and spiritual orientation

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Preface

As the twenty-first century unfolds, it is becoming more and more evident that the major problems of our time – energy, the environment, climate change, food security, financial security – cannot be understood in isolation. They are systemic problems, which means that they are all interconnected and interdependent. Ultimately, these problems must be seen as just different facets of one single crisis, which is largely a crisis of perception. It derives from the fact that most people in our modern society, and especially our large social institutions, subscribe to the concepts of an outdated worldview, a perception of reality inadequate for dealing with our overpopulated, globally interconnected world.

There *are* solutions to the major problems of our time; some of them even simple. But they require a radical shift in our perceptions, our thinking, our values. And, indeed, we are now at the beginning of such a fundamental change of worldview in science and society, a change of paradigms as radical as the Copernican revolution. Unfortunately, this realization has not yet dawned on most of our political leaders, who are unable to "connect the dots," to use a popular phrase. They fail to see how the major problems of our time are all interrelated. Moreover, they refuse to recognize how their so-called solutions affect future generations. From the systemic point of view, the only viable solutions are those that are sustainable. As we discuss in this book, a sustainable society must be designed in such a way that its ways of life, businesses, economy, physical structures, and technologies do not interfere with nature's inherent ability to sustain life.

Over the past thirty years it has become clear that a full understanding of these issues requires nothing less than a radically new conception of life. And indeed, such a new understanding of life is now emerging. At the forefront of contemporary science, we no longer see 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; that 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 no longer seen 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. And with the new emphasis on complexity, networks, and patterns of organization, a new science of qualities is slowly emerging.

This new conception of life involves a new kind of thinking – thinking in terms of relationships, patterns, and context. In science, this way of thinking is known as "systemic thinking," or "systems thinking"; hence, the understanding of life that is informed by it is often identified by the phrase we have chosen for the title of this book: the systems view of life.

The new scientific understanding of life encompasses many concepts and ideas that are being developed by outstanding researchers and their teams around the world. With the present book, we want to offer an interdisciplinary text that integrates these ideas, models, and theories into a single coherent framework. We present a unified systemic vision that includes and integrates life's biological, cognitive, social, and ecological dimensions; and we also discuss the philosophical, spiritual, and political implications of our unified view of life.

We believe that such an integrated view is urgently needed today to deal with our global ecological crisis and protect the continuation and flourishing of life on Earth. It will therefore be critical for present and future generations of young researchers and graduate students to understand the new systemic conception of life and its implications for a broad range of professions – from economics, management, and politics to medicine, psychology, and law. In addition, our book will be useful for undergraduate students in the life sciences and the humanities.

In the following chapters, we take a broad sweep through the history of ideas and across scientific disciplines. Beginning with the Renaissance and the Scientific Revolution, our historical account includes the evolution of Cartesian mechanism from the seventeenth to the twentieth centuries, the rise of systems thinking, the development of complexity theory, recent discoveries at the forefront of biology, the emergence of the new conception of life at the turn of this century, and its economic, ecological, political, and spiritual implications.

The reader will notice that our text includes not only numerous references to the literature, but also an abundance of cross-references to chapters and sections in this book. There is a good reason for this abundance of references. A central characteristic of the systems view of life is its nonlinearity: all living systems are complex – i.e., highly nonlinear – networks; and there are countless interconnections between the biological, cognitive, social, and ecological dimensions of life. Thus, a conceptual framework integrating these multiple dimensions is bound to reflect life's inherent nonlinearity. In our struggle to communicate such a complex network of concepts and ideas within the linear constraints of written language, we felt that it would help to interconnect the text by a network of cross-references. Our hope is that the reader will find that, like the web of life, this book itself is also a whole that is more than the sum of its parts.

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The synthesis of concepts and ideas we present in this book took three decades to mature. During this time, we were fortunate to be able to discuss most of the underlying scientific models and theories with their authors and with other scientists working in those fields, as well as with each other. Many of our insights and ideas originated and were further refined in those intellectual encounters.

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Introduction: paradigms in science and society

Questions about the origin, nature, and meaning of life are as old as humanity itself. Indeed, they lie at the very roots of philosophy and religion. The earliest school of Greek philosophy, known as the Milesian school, made no distinction between animate and inanimate, nor between spirit and matter. Later on, the Greeks called those early philosophers "hylozoists," or "those who think that matter is alive."

The ancient Chinese philosophers believed that the ultimate reality, which underlies and unifies the multiple phenomena we observe, is intrinsically dynamic. They called it *Tao* – the way, or process, of the universe. For the Taoist sages all things, whether animate or inanimate, were embedded in the continuous flow and change of the *Tao*. The belief that everything in the universe is imbued with life has also been characteristic of indigenous spiritual traditions throughout the ages. In monotheistic religions, by contrast, the origin of life is associated with a divine creator.

In this book, we shall approach the age-old questions of the origin and nature of life from the perspective of modern science. We shall see that even within that much narrower context the distinction between living and nonliving matter is often problematic and somewhat arbitrary. Nevertheless, modern science has shown that the vast majority of living organisms exhibit fundamental characteristics that are strikingly different from those of nonliving matter.

To fully appreciate both the achievements and limitations of the new scientific conception of life – the subject of this book – it will be useful first to clarify the nature and limitations of science itself. The modern word "science" is derived from the Latin *scientia*, which means "knowledge," a meaning that was retained throughout the Middle Ages, the Renaissance, and the era of the Scientific Revolution. What we call "science" today was known as "natural philosophy" in those earlier epochs. For example, the full title of the *Principia*, Isaac Newton's famous work, published in 1687, which became the foundation of science in subsequent centuries, was *Philosophiae naturalis principia mathematica* ("The Mathematical Principles of Natural Philosophy").

The modern meaning of science is that of an organized body of knowledge acquired through a particular method known as the scientific method. This modern understanding evolved gradually during the eighteenth and nineteenth centuries. The characteristics of the scientific method were fully recognized only in the twentieth century and are still frequently misunderstood, especially by nonscientists.

The scientific method

The scientific method represents a particular way of gaining knowledge about natural and social phenomena, which can be summarized as occurring in several stages.

First, it involves the systematic observation of the phenomena being studied and the recording of these observations as evidence, or scientific data. In some sciences, such as physics, chemistry, and biology, the systematic observation includes controlled experiments; in others, such as astronomy or paleontology, this is not possible.

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

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

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

Crucial to the contemporary understanding of science is the realization that all scientific models and theories are limited and approximate (as we discuss more fully in Chapter 4). Twentieth-century science has shown repeatedly that all natural phenomena are ultimately interconnected, and that their essential properties, in fact, derive from their relationships to other things. Hence, in order to explain any one of them completely, we would have to understand all the others, and that is obviously impossible.

What makes the scientific enterprise feasible is the realization that, although science can never provide complete and definitive explanations, limited and approximate scientific knowledge is possible. This may sound frustrating, but for many scientists the fact that we *can* formulate approximate models and theories to describe an endless web of interconnected phenomena, and that we are able to systematically improve our models or approximations over time, is a source of confidence and strength. As the great biochemist Louis Pasteur (quoted by Capra, 1982) put it:

> Science advances through tentative answers to a series of more and more subtle questions which reach deeper and deeper into the essence of natural phenomena.

Scientific and social paradigms

During the first half of the twentieth century, philosophers and historians of science generally believed that progress in science was a smooth process in which scientific models and theories were continually refined and replaced by new and more accurate versions, as their approximations were improved in successive steps. This view of continuous progress was radically challenged by the physicist and philosopher of science Thomas Kuhn (1962) in his influential book, *The Structure of Scientific Revolutions*.

Kuhn argued that, while continuous progress is indeed characteristic of long periods of "normal science," these periods are interrupted by periods of "revolutionary science" in which not only a scientific theory but also the entire conceptual framework in which it is embedded undergoes radical change. To describe this underlying framework, Kuhn introduced the concept of a scientific "paradigm," which he defined as a constellation of achievements – concepts, values, techniques, etc. – shared by a scientific community and used by that community to define legitimate problems and solutions. Changes of paradigms, according to Kuhn, occur in discontinuous, revolutionary breaks called "paradigm shifts."

Kuhn's work has had an enormous impact on the philosophy of science, as well as on the social sciences. Perhaps the most important aspect of his definition of a scientific paradigm is the fact that it includes not only concepts and techniques but also values. According to Kuhn, values are not peripheral to science, nor to its applications to technology, but constitute their very basis and driving force.

During the Scientific Revolution in the seventeenth century, values were separated from facts (as we discuss in Chapter 1), and ever since that time scientists have tended to believe that scientific facts are independent of what we do and are therefore independent of our values. Kuhn exposed the fallacy of that belief by showing that scientific facts emerge out of an entire constellation of human perceptions, values, and actions – out of a paradigm – from which they cannot be separated. Although much of our detailed research may not depend explicitly on our value system, the larger paradigm within which this research is pursued will never be value-free. As scientists, therefore, we are responsible for our research not only intellectually but also morally.

During the past decades, the concepts of "paradigm" and "paradigm shift" have been used increasingly also in the social sciences, as social scientists realized that many characteristics of paradigm shifts can be observed also in the larger social arena. To analyze those broader social and cultural transformations, Capra (1996, p. 6) generalized Kuhn's definition of a scientific paradigm to that of a social paradigm, defining it as "a constellation of concepts, values, perceptions, and practices shared by a community, which forms a particular vision of reality that is the basis of the way the community organizes itself."

The emerging new scientific conception of life, which we summarized in our Preface, can be seen as part of a broader paradigm shift from a mechanistic to a holistic and ecological worldview. At its very core we find a shift of metaphors that is now becoming ever more apparent, as discussed by Capra (2002) – a change from seeing the world as a machine to understanding it as a network.

During the twentieth century, the change from the mechanistic to the ecological paradigm proceeded in different forms and at different speeds in various scientific fields. It has not been a steady change, but has involved scientific revolutions, backlashes, and pendulum swings. A chaotic pendulum in the sense of chaos theory (discussed in Chapter 6) – oscillations that almost repeat themselves but not quite, seemingly random and yet forming a complex, highly organized pattern – would perhaps be the most appropriate contemporary metaphor.

The basic tension is one 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 "systems thinking," as we have mentioned.

In biology, the tension between mechanism and holism has been a recurring theme throughout its history. At the dawn of Western philosophy and science, the Pythagoreans distinguished "number," or pattern, from substance, or matter, viewing it as something which limits matter and gives it shape. The argument was: do you ask what it is made of – earth, fire, water, etc. – or do you ask what its *pattern* is?

Ever since early Greek philosophy, there has been this tension between substance and pattern. Aristotle, the first biologist in the Western tradition, distinguished between four causes as interdependent sources of all phenomena: the material cause, the formal cause, the efficient cause, and the final cause. The first two causes refer to the two perspectives of substance and pattern which, following Aristotle, we shall call the perspective of matter and the perspective of form.

The study of matter begins with the question, "What is it made of?" This leads to the notions of fundamental elements, building blocks; to measuring and quantifying. The study of form asks, "What is the pattern?" And that leads to the notions of order, organization, and relationships. Instead of quantity, it involves quality; instead of measuring, it involves mapping.

These are two very different lines of investigation that have been in competition with one another throughout our scientific and philosophical tradition. For most of the time, the study of matter – of quantities and constituents – has dominated. But every now and then the study of form – of patterns and relationships – came to the fore.

It is also worth noting that ancient Chinese philosophy and science were always more concerned with the interrelations between things than with their reduction to a fundamental substance. In the words of the distinguished sinologist Joseph Needham (1962, p. 478), "While European philosophy tended to find reality in substance, Chinese philosophy tended to find it in relation."

Pendulum swings between mechanism and holism: from antiquity to the modern era

Let us now very briefly follow the swings of this chaotic pendulum between mechanism and holism through the history of biology. For the ancient Greek philosophers, the world was a *kosmos*, an ordered and harmonious structure. From its beginnings in the sixth century BC, Greek philosophy and science understood the order of the cosmos to be that of a living organism rather than a mechanical system. This meant for them that all its parts had an innate purpose to contribute to the harmonious functioning of the whole, and that objects moved naturally toward their proper places in the universe. Such an explanation of natural phenomena in terms of their goals, or purposes, is known as teleology, from the Greek *telos* ("purpose"). It permeated virtually all of Greek philosophy and science.

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

In early Greek philosophy, the ultimate moving force and source of all life was identified with the soul, and its principal metaphor was that of the breath of life.

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

As far as the composition of matter was concerned, Empedocles (fifth century BC) claimed that the material world was composed of varying combinations of the four elements – earth, water, air, and fire. When left to themselves, the elements would settle into concentric spheres with the Earth at the center, surrounded successively by the spheres of water, air, and fire (or light). Further outside were the spheres of the planets and beyond them was the sphere of the stars.

Half a century after Empedocles, an alternative theory of matter was proposed by Democritus, who taught that all material objects were composed of atoms of numerous shapes and sizes, and that all observable qualities derived from the particular combinations of atoms inside the objects. His theory was so antithetical to the traditional teleological views of matter that it was pushed into the background, where it remained throughout the Middle Ages and the Renaissance. It would only surface again in the seventeenth century, with the rise of Newtonian physics.

The teachings of Democritus (460–340 BC) were expanded by Epicurus (341–270 BC), also an atomist, who restated that everything that occurs is the result of the recombination of atoms, and that there is no purpose behind their motions, nor any design of the gods. Epicurus had a great follower in the first century BC in the Roman poet Lucretius, whose poem *De Rerum Natura* is a remarkable exposition of the science of his time, also with a strong atheist flavor.

For the history of science in the subsequent centuries, the most important Greek philosopher was Aristotle (fourth century BC). He was the first philosopher to write systematic, professorial treatises about the main branches of learning of his time. He synthesized and organized the entire scientific knowledge of antiquity in a scheme that would remain the foundation of Western science for 2,000 years.

Aristotle's treatises were the foundation of philosophical and scientific thought in the Middle Ages and the Renaissance. Christian medieval philosophers, unlike their Arab counterparts, did not use Aristotle's texts as a basis for their own independent research, but instead evaluated them from the perspective of Christian theology. Indeed, most of them were theologians, and their practice of combining philosophy – including natural philosophy, or science – with theology became known as scholasticism.

The leading figure in this movement to weave the philosophy of Aristotle into the Christian teachings was Thomas Aquinas (1225–1274), one of the towering intellects of the Middle Ages. Aquinas taught that there could be no conflict between faith and reason, because the two books on which they were based – the Bible and the "book of nature" – were both authored by God. He produced a vast body of precise, detailed, and systematic philosophical writings, in which he integrated Aristotle's encyclopedic works and medieval Christian theology into a seamless whole.

The dark side of this fusion of science and theology was that any contradiction by future scientists would necessarily have to be seen as heresy. In this way, Thomas Aquinas enshrined in his writings the potential for conflicts between science and religion – which reached a dramatic climax with the trial of Galileo, and have continued to the present day.

Between the Middle Ages and the modern era lies the Renaissance, a period stretching from the beginning of the fifteenth to the end of the sixteenth century. It was a period of intense explorations – of ancient intellectual ideas and of new geographical regions of the Earth. The intellectual climate of the Renaissance was decisively shaped by the philosophical and literary movement of humanism, which made the capabilities of the human individual its central concern. This was a fundamental shift from the medieval dogma of understanding human nature from a religious point of view. The Renaissance offered a more secular outlook, with heightened focus on the individual human intellect.

The new spirit of humanism expressed itself through a strong emphasis on classical studies. During the Middle Ages, much of Greek philosophy, and science had been forgotten in Western Europe, while the classical texts were translated and examined by Arab scholars. Their rediscovery and translation into Latin from Greek and Arabic greatly extended the intellectual frontiers of the European humanists. Scholars and artists were exposed to the great diversity of Greek and Roman philosophical ideas that encouraged individual critical thought and prepared the ground for the gradual emergence of a rational, scientific frame of mind.

According to Capra (2007), modern scientific thought did not emerge with Galileo, as is usually stated by historians of science, but with Leonardo da Vinci (1452–1519). One hundred years before Galileo and Francis Bacon, Leonardo single-handedly developed a new empirical approach, involving the systematic observation of nature, reasoning, and mathematics – in other words, the main characteristics of the scientific method. But his science was radically different from the mechanistic science that would emerge 200 years later. It was a science of organic forms, of qualities, of processes of transformation.

Leonardo's approach to scientific knowledge was visual; it was the approach of the painter. He asserted repeatedly that painting involves the study of natural forms, and he emphasized the intimate connection between the artistic representation of those forms and the intellectual understanding of their intrinsic nature and underlying principles. Thus he created a unique synthesis of art and science, unequalled by any artist before him or since.

Many aspects of Leonardo's science are still Aristotelian, but what makes it sound so modern to us today is that his forms are living forms, continually shaped and transformed by underlying processes. Throughout his life he studied, drew, and painted the rocks and strata of the Earth, shaped by erosion; the growth of plants, shaped by their metabolism; and the anatomy of the animal body in motion.

Leonardo did not pursue science and engineering to dominate nature, as Francis Bacon would advocate a century later, but always tried to learn from her as much as possible. He was in awe of the beauty he saw in the complexity of natural forms, patterns, and processes, and aware that nature's ingenuity was far superior to human design. Accordingly, he often used natural processes and structures as models for his designs. This attitude of seeing nature as a model and mentor is now advanced again, 500 years after Leonardo, in the practice of ecological design (see Section 18.4).

Leonardo's scientific work was virtually unknown during his lifetime, and his manuscripts remained hidden for over two centuries after his death in 1519. Thus his pioneering discoveries and ideas had no direct influence on the further development of science. Eventually, they were all rediscovered by other scientists, often hundreds of years later.

A century after Leonardo's science of qualities and living forms, the pendulum swung in the other direction – toward quantities and a mechanistic conception of nature. In the sixteenth and seventeenth centuries the medieval worldview, based on Aristotelian philosophy and Christian theology, changed radically. The notion of an organic, living, and spiritual universe was replaced by that of the world as a machine, and the world-machine became the dominant metaphor of the modern era until the late twentieth century when it began to be replaced by the metaphor of the network.

The rise of the mechanistic worldview was brought about by revolutionary changes in physics and astronomy, culminating in the achievements of Copernicus, Kepler, Galileo, Bacon, Descartes, and Newton. Because of the crucial role of science in bringing about these far-reaching changes, historians have called the sixteenth and seventeenth centuries the age of the Scientific Revolution.

Galileo Galilei (1564–1642) postulated that, in order to be effective in describing nature mathematically, scientists should restrict themselves to studying those properties of material bodies – shapes, numbers, and movement – which could be measured and quantified. Other properties, like color, sound, taste, or smell, were merely subjective mental projections which should be excluded from the domain of science.

Galileo's strategy of directing the scientist's attention to the quantifiable properties of matter proved extremely successful in physics, but it also exacted a heavy toll. During the centuries after Galileo, the focus on quantities was extended from the study of matter to all natural and social phenomena within the framework of the mechanistic worldview of Cartesian-Newtonian science. By excluding colors, sound, taste, touch, and smell – let alone more complex qualities, such as beauty, health, or ethical sensibility – the emphasis on quantification prevented scientists for several centuries from understanding many essential properties of life.

While Galileo devised ingenious experiments in Italy, in England Francis Bacon (1561–1626) set forth the empirical method of science explicitly, as Leonardo da Vinci had done a century before him. Bacon formulated a clear theory of the inductive procedure – to make experiments and to draw conclusions from them, to be tested by further experiments – and he became extremely influential by vigorously advocating the new method.

The shift from the organic to the mechanistic worldview was initiated by one of the towering figures of the seventeenth century, René Descartes (1596–1650). Descartes, or Cartesius (his Latinized name), is usually regarded as the founder of modern philosophy, and he was also a brilliant mathematician and a very influential scientist. Descartes based his view of nature on the fundamental division between two independent and separate realms – that of mind and that of matter. The material universe, including living organisms, was a machine for him, which could in principle be understood completely by analyzing it in terms of its smallest parts.

The conceptual framework created by Galileo and Descartes – the world as a perfect machine governed by exact mathematical laws – was completed triumphantly by Isaac Newton (1642–1727), whose grand synthesis, Newtonian mechanics, was the crowning achievement of seventeenth-century science. In biology, the greatest success of Descartes' mechanistic model was its application to the phenomenon of blood circulation by William Harvey, a contemporary of Descartes. Physiologists of that time also tried to describe other bodily functions, such as digestion, in mechanistic terms, but these attempts were bound to fail because of the chemical nature of the processes, which was not yet understood.

With the development of chemistry in the eighteenth century, the simplistic mechanical models of living organisms were largely abandoned, but the essence of the Cartesian idea survived. Animals were still viewed as machines, albeit much more complicated ones than mechanical clockworks, since they involved complex chemical processes. Accordingly, Cartesian mechanism was expressed in the dogma that the laws of biology can ultimately be reduced to those of physics and chemistry.

Mechanism and holism in modern biology

The first strong opposition to the mechanistic Cartesian paradigm came from the Romantic movement in art, literature, and philosophy in the late eighteenth and early nineteenth centuries. William Blake (1757–1827), the great mystical poet and painter who exerted a strong influence on English Romanticism, was a passionate critic of Newton. He summarized his critique in the celebrated lines (quoted by Capra, 1996):

> May God us keep
> From single vision and Newton's sleep.

In Germany, Romantic poets and philosophers concentrated on the nature of organic form, as Leonardo da Vinci had done 300 years earlier. Johann Wolfgang von Goethe (1749–1832), the central figure in this movement, was among the first to use the term "morphology" for the study of biological form from a dynamic, developmental point of view. He conceived of form as a pattern of relationships within an organized whole – a conception which is at the forefront of systems thinking today.

The Romantic view of nature as "one great harmonious whole," as Goethe put it, led some scientists of that period to extend their search for wholeness to the entire planet and see the Earth as an integrated whole, a living being. In doing so, they revived an ancient tradition that had flourished throughout the Middle Ages and the Renaissance, until the medieval outlook was replaced by the Cartesian image of the world as a machine. In other words, the view of the Earth as a living being had been dormant for only a relatively brief period.

More recently, the idea of a living planet was formulated in modern scientific language as the so-called Gaia theory. The views of the living Earth developed by Leonardo da Vinci in the fifteenth century and by the Romantic scientists in the eighteenth contain some key elements of our contemporary Gaia theory.

At the turn of the eighteenth to the nineteenth century, the influence of the Romantic movement was so strong that the primary concern of biologists was the problem of biological form, and questions of material composition were secondary. This was especially true for the great French schools of comparative anatomy, or morphology, pioneered by Georges Cuvier (1769–1832), who created a system of zoological classification based on similarities of structural relations.

During the second half of the nineteenth century, the pendulum swung back to mechanism, when the newly perfected microscope led to many remarkable advances in biology. The nineteenth century is best known for the emergence of evolutionary thought, but it also saw the formulation of cell theory, the beginning of modern embryology, the rise of microbiology, and the discovery of the laws of heredity. These new discoveries grounded biology firmly in physics and chemistry, and scientists renewed their efforts to search for physico-chemical explanations of life.

When Rudolf Virchow (1821–1902) formulated cell theory in its modern form, the focus of biologists shifted from organisms to cells. Biological functions, rather than reflecting the organization of the organism as a whole, were now seen as the results of interactions at the cellular level. Research in microbiology was dominated by Louis Pasteur (1822–1895), who was able to establish the role of bacteria in certain chemical processes, thus laying the foundations of biochemistry. Moreover, Pasteur demonstrated that there is a definite correlation between microorganisms and disease.

As the new science of biochemistry progressed, it established the firm belief among biologists that all properties and functions of living organisms would eventually be explained in terms of chemical and physical laws. Indeed, cell biology made enormous progress in understanding the structures and functions of many of the cell's subunits. However, it advanced very little in understanding the coordinating activities that integrate those phenomena into the functioning of the cell as a whole. At the turn of the nineteenth century, the awareness of this lack of understanding triggered the next wave of opposition to the mechanistic conception of life, the school known as organismic biology, or "organicism."

During the early twentieth century, organismic biologists took up the problem of biological form with new enthusiasm, elaborating and refining many of the key insights of Aristotle, Goethe, and Cuvier. Their extensive reflections helped to give birth to a new way of thinking – "systems thinking" – in terms of connectedness, relationships, and context. According to the systems view, an organism, or living system, is an integrated whole whose essential properties cannot be reduced to those of its parts. They arise from the interactions and relationships between the parts.

When organismic biologists in Germany explored the concept of organic form, they engaged in dialogues with psychologists from the very beginning. The philosopher Christian von Ehrenfels (1859–1932) used the German word *Gestalt*, meaning "organic form," to describe an irreducible perceptual pattern, which sparked the school of Gestalt psychology. To characterize a Gestalt, Ehrenfels used the phrase, "The whole is more than the sum of its parts," which would become the catchphrase of systems thinking later on. The origin of this celebrated phrase is to be found in Aristotle's *Metaphysics*: "In the case of all things which have several parts . . . the whole is not, as it were, a mere heap, but the totality is something besides the parts" (see Barnes, 1984, vol. 2, p. 1650).

While organismic biologists encountered irreducible wholeness in organisms, and Gestalt psychologists in perception, ecologists encountered it in their studies of animal and plant communities. The new science of ecology emerged out of organismic biology during the late nineteenth century, when biologists began to study communities of organisms.

In the 1920s, ecologists introduced the concepts of food chains and food cycles, which were subsequently expanded to the contemporary concept of food webs. In addition, they developed the notion of the ecosystem, which, by its very name, fostered a systems approach to ecology.

By the end of the 1930s, most of the key criteria of systems thinking had been formulated by organismic biologists, Gestalt psychologists, and ecologists (see Section 4.3 below). The 1940s saw the formulation of actual systems theories. This means that systemic concepts were integrated into coherent theoretical frameworks describing the principles of organization of living systems. These first theories, which we may call the "classical systems theories," include, in particular, general systems theory and cybernetics. As we discuss in Chapter 5, general systems theory was developed by a single scientist, the biologist Ludwig von Bertalanffy, while the theory of cybernetics was the result of a multidisciplinary collaboration between mathematicians, neuroscientists, social scientists, and engineers – a group that became known collectively as the cyberneticists.

During the 1950s and 1960s, systems thinking had a strong influence on engineering and management, where systemic concepts – including those of cybernetics – were applied to solve practical problems. Yet, paradoxically, the influence of the systems approach in biology was almost negligible during that time.

The 1950s was the decade of the spectacular triumph of genetics, the elucidation of the physical structure of DNA and of the genetic code. For several decades, this triumphal success totally eclipsed the systems view of life. Once again, the pendulum swung back to mechanism.

The achievements of genetics brought about a significant shift in biological research, a new perspective which still dominates our academic institutions today. Whereas cells were regarded as the basic building blocks of living organisms during the nineteenth century, the attention shifted from cells to molecules toward the middle of the twentieth century, when geneticists began to explore the molecular structure of the gene.

Advancing to ever smaller levels in their explorations of the phenomena of life, biologists found that the characteristics of all living organisms – from bacteria to humans – were encoded in their chromosomes in the same chemical substance, using the same code script.

This triumph of molecular biology resulted in the widespread belief that all biological functions can be explained in terms of molecular structures and mechanisms. At the same time, the problems that resist the mechanistic approach of molecular biology became ever more apparent. While biologists knew the precise structure of a few genes, they knew very little of the ways in which genes communicate and cooperate in the development of an organism. In other words, molecular biologists realized that they knew the alphabet of the genetic code but had almost no idea of its syntax.

By the mid 1970s, the limitations of the molecular approach to the understanding of life were evident. However, biologists saw little else on the horizon. The eclipse of systems thinking from pure science had become so complete that it was not considered a viable alternative. In fact, systems theory began to be seen as an intellectual failure in several critical essays. One reason for this harsh assessment was that Ludwig von Bertalanffy (1968) had announced in a rather grandiose manner that his goal was to develop general systems theory into "a mathematical discipline, in itself purely formal but applicable to the various empirical sciences." He could never achieve this ambitious goal because in his time no mathematical techniques were available to deal with the enormous complexity of living systems. Bertalanffy recognized that the patterns of organization characteristic of life are generated by the simultaneous interactions of a large number of variables, but he lacked the means to describe the emergence of those patterns mathematically. Technically speaking, the mathematics of his time was limited to linear equations, which are inappropriate to describe the highly nonlinear nature of living systems.

The cyberneticists did concentrate on nonlinear phenomena like feedback loops and neural networks, and they had the beginnings of a corresponding nonlinear mathematics, but the real breakthrough came several decades later with the formulation of complexity theory, technically known as "nonlinear dynamics," in the 1960s and 1970s (see Chapter 6). The decisive advance was due to the development of powerful, high-speed computers, which allowed scientists and mathematicians for the first time to model the nonlinear interconnectedness characteristic of living systems, and to solve the corresponding nonlinear equations.

During the 1980s and 1990s, complexity theory generated great excitement in the scientific community. In biology, systems thinking and the organic conception of life reappeared on the scene, and the strong interest in nonlinear phenomena generated a whole series of new and powerful theoretical models that have dramatically increased our understanding of many key characteristics of life. From these models the outlines of a coherent theory of living systems, together with the proper mathematical language, are now emerging. This emerging theory – the systems view of life – is the subject of this book.

Deep ecology

The new scientific understanding of life at all levels of living systems – organisms, social systems, and ecosystems – is based on a perception of reality that has profound implications not only for science and philosophy, but also for politics, business, healthcare, education, and many other areas of everyday life. It is therefore appropriate to end our Introduction with a brief discussion of the social and cultural context of the new conception of life.

As we have mentioned, the *Zeitgeist* ("spirit of the age") of the early twenty-first century is being shaped by a profound change of paradigms, characterized by a shift of metaphors from the world as a machine to the world as a network. The new paradigm may be called a holistic worldview, seeing the world as an integrated whole rather than a dissociated collection of parts. It may also be called an ecological view, if the term "ecological" is used in a much broader and deeper sense than usual. Deep ecological awareness recognizes the fundamental interdependence of all phenomena and the fact that, as individuals and societies, we are all embedded in (and ultimately dependent on) the cyclical processes of nature.

The sense in which we use the term "ecological" is associated with a specific philosophical school, founded in the early 1970s by the Norwegian philosopher Arne Naess (1912–2009) with the distinction between "shallow" and "deep" ecology (see Devall and Sessions, 1985). Since then, this distinction has been widely accepted as a very useful term for referring to a major division within contemporary environmental thought.

Shallow ecology is anthropocentric, or human-centered. It views humans as above or outside of nature, and as the source of all value, and ascribes only instrumental, or "use," value to nature. Deep ecology does not separate humans – or anything else – from the natural environment. It sees the world not as a collection of isolated objects but as a network of phenomena that are fundamentally interconnected and interdependent. Deep ecology recognizes the intrinsic value of all living beings and views humans as just one particular strand in the web of life.

Ultimately, deep ecological awareness is spiritual awareness. When the concept of the human spirit is understood as the mode of consciousness in which the individual feels a sense of belonging, of connectedness, to the cosmos as a whole, it becomes clear that ecological awareness is spiritual in its deepest essence. Hence, the emerging new vision of reality, based on deep ecological awareness, is consistent with the so-called "perennial philosophy" of spiritual traditions, as we discuss in Chapter 13.

There is another way in which Arne Naess characterized deep ecology. "The essence of deep ecology," he wrote, "is to ask deeper questions" (quoted by Devall and Sessions, 1985, p. 74). This is also the essence of a paradigm shift. We need to be prepared to question every single aspect of the old paradigm. Eventually, we will not need to abandon all our old concepts and ideas, but before we know that, we need to be willing to question everything. So, deep ecology asks profound questions about the very foundations of our modern, scientific, industrial, growth-oriented, materialistic worldview and way of life. It questions this entire paradigm from an ecological perspective: from the perspective of our relationships to one another, to future generations, and to the web of life of which we are part.

In our brief summary of the emerging systems view of life in the Preface, we have emphasized shifts in perceptions and ways of thinking. However, the broader paradigm shift also involves corresponding changes of values. And here it is interesting to note a striking connection between the changes of thinking and of values. Both of them may be seen as shifts from self-assertion to integration. These two tendencies – the self-assertive and the integrative – are both essential aspects of all living systems, as we discuss in Chapter 4 (Section 4.1.2). Neither of them is intrinsically good or bad. What is good, or healthy, is a dynamic balance; what is bad, or unhealthy, is imbalance – overemphasis on one tendency and neglect of the other. When we look at our modern industrial culture, we see that we have overemphasized the self-assertive and neglected the integrative tendencies. This is apparent both in our thinking and in our values. It is very instructive to put these opposite tendencies side by side.

thinking		values	
self-assertive	integrative	self-assertive	integrative
rational	intuitive	expansion	conservation
analysis	synthesis	competition	cooperation
reductionist	holistic	quantity	quality
linear	nonlinear	domination	partnership

When we look at this table, we notice that the self-assertive values – competition, expansion, domination – are generally associated with men. Indeed, in patriarchal societies they are not only favored but also given economic rewards and political power. This is one of the reasons why the shift to a more balanced value system is so difficult for most people, and especially for most men.

Power, in the sense of domination over others, is excessive self-assertion. The social structure in which it is exerted most effectively is the hierarchy. Indeed, our political, military, and corporate structures are hierarchically ordered, with men generally occupying the upper levels and women the lower. Most of these men, and also quite a few women, have come to see their position in the hierarchy as part of their identity, and thus the shift to a different system of values generates existential fears in them.

However, there is another kind of power, one that is more appropriate for the new paradigm – power as empowerment of others. The ideal structure for exerting this kind of power is not the hierarchy but the network, the central metaphor of the ecological paradigm. In a social network, people are empowered by being connected to the network. Power as empowerment means facilitating this connectedness. The network hubs with the richest connections become centers of power. They connect large numbers of people to the network and are therefore sought out as authorities in various fields. Their authority allows these centers to empower people by connecting more of the network to itself.

The question of values is crucial to deep ecology. In fact, it is its defining characteristic. Whereas the mechanistic paradigm is based on anthropocentric (human-centered) values, deep ecology is grounded in ecocentric (Earth-centered) values. It is a worldview that acknowledges the inherent value of nonhuman life, recognizing that all living beings are members of ecological communities, bound together in networks of interdependencies. When this deep ecological perception becomes part of our daily awareness, a radically new system of ethics emerges.

Such a deep ecological ethic is urgently needed today, especially in science, since most of what scientists do is not life-furthering and life-preserving but life-destroying. With physicists designing weapons systems of mass destruction, chemists contaminating the global environment, biologists releasing new and unknown types of microorganisms without knowing the consequences, psychologists and other scientists torturing animals in the name of scientific progress – with all these activities going on, it seems most urgent to introduce "eco-ethical" standards into science.

Within the context of deep ecology, the view that values are inherent in all of living nature is based on the spiritual experience that nature and the self are one. This expansion of the self all the way to the identification with nature is the proper grounding of ecological ethics, as Arne Naess clearly recognized:

> Care flows naturally if the "self" is widened and deepened so that protection of free Nature is felt and conceived as protection of ourselves . . . Just as we need no morals to make us breathe . . . [so] if your "self" in the wide sense embraces another being, you need no moral exhortation to show care . . . You care for yourself without feeling any moral pressure to do it.
>
> *(quoted by Fox, 1990, p. 217)*

What this implies, according to the eco-philosopher Warwick Fox (1990), is that the connection between an ecological perception of the world and corresponding behavior is not a logical but a psychological connection. Logic does not lead us from the fact that we are an integral part of the web of life to certain norms of how we should live. However, if we have the deep ecological experience of being part of the web of life, then we *will* (as opposed to *should*) be inclined to care for all of living nature. Indeed, we can scarcely refrain from responding in this way.

By calling the emerging new vision of reality "ecological" in the sense of deep ecology, we emphasize that life is at its very center. This is an important issue for science, because in the mechanistic paradigm physics has been the model and source of metaphors for all other sciences. "All philosophy is like a tree," wrote Descartes (quoted by Vrooman, 1970, p. 189). "The roots are metaphysics, the trunk is physics, and the branches are all the other sciences."

The systems view of life has overcome this Cartesian metaphor. Physics, together with chemistry, is essential to understand the behavior of the molecules in living cells, but it is not sufficient to describe their self-organizing patterns and processes. At the level of living systems, physics has thus lost its role as the science providing the most fundamental description of reality. This is still not generally recognized today. Scientists as well as nonscientists frequently retain the popular belief that "if you really want to know the ultimate explanation, you have to ask a physicist," which is clearly a Cartesian fallacy. The paradigm shift in science, at its deepest level, involves a perceptual shift from physics to the life sciences.

I

The mechanistic worldview

1

The Newtonian world-machine

To appreciate the revolutionary nature of the systems view of life, it is useful to examine in some detail the history, principal characteristics, and widespread influence of the mechanistic paradigm, which it is destined to replace. This is the purpose of our first three chapters, in which we discuss the origin and rise of Cartesian-Newtonian science during the Scientific Revolution (Chapter 1), as well as its impact on both the life sciences (Chapter 2) and the social sciences (Chapter 3).

The worldview and value system that lie at the basis of the modern industrial age were formulated in their essential outlines in the sixteenth and seventeenth centuries. Between 1500 and 1700, there was a dramatic shift in the way people in Europe pictured the world and in their whole way of thinking. The new mentality and new perception of the cosmos gave our Western civilization the features that are characteristic of the modern era. They became the basis of the paradigm that has dominated our culture for the past 300 years and is now changing.

Before 1500, the dominant worldview in European civilization, as well as in most other civilizations, was organic. People lived in small, cohesive communities and experienced nature in terms of personal relationships, characterized by the interdependence of spiritual and material concerns and the subordination of individual needs to those of the community.

The scientific framework of this organic worldview rested on two authorities – Aristotle and the Church. In the thirteenth century, Thomas Aquinas had combined Aristotle's comprehensive system of nature with Christian theology and ethics, and, in doing so, had established the framework that remained unquestioned throughout the Middle Ages. The nature of medieval science was very different from that of our contemporary science. It was based on both reason and faith, and its main goal was to understand the meaning and significance of things, rather than prediction and control. Medieval scientists, looking for the purposes underlying various natural phenomena, considered questions relating to God, the human soul, and ethics to be of the highest significance.

During the sixteenth and seventeenth centuries, the medieval outlook changed radically. The notion of an organic, living, and spiritual universe was replaced by that of the world as a machine, and the mechanistic conception of reality became the basis of the modern worldview. This development was brought about by revolutionary changes in physics and astronomy, culminating in the achievements of Copernicus, Galileo, and Newton.

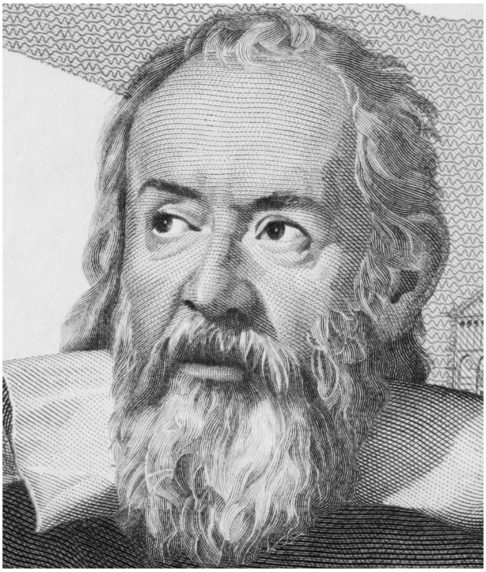

Figure 1.1 Galileo Galilei (1564–1642). iStockphoto.com/© Georgios Kollidas.

Seventeenth-century science was based on the new empirical method of inquiry advocated forcefully by Francis Bacon, and it included the mathematical description of nature and analytic method of reasoning conceived by the genius of Descartes.

1.1 The Scientific Revolution

The Scientific Revolution began with Nicolaus Copernicus (1473–1543), who overthrew the geocentric view of Ptolemy and the Bible that had been accepted dogma for more than a thousand years. After Copernicus, the Earth was no longer the center of the universe but merely one of many planets circling a minor star at the edge of the galaxy, and humanity was robbed of its proud position as the center of God's creation. Copernicus was fully aware that his view would deeply offend the religious consciousness of his time. He delayed the publication of his epochal book, *De revolutionibus orbium coelestium* ("On the Revolution of the Celestial Spheres"), until 1543, the year of his death, and even then he presented the heliocentric view merely as a hypothesis.

Copernicus was followed by Johannes Kepler (1571–1630), a scientist and mystic who searched for the harmony of the spheres and was able, through painstaking work with astronomical tables, to formulate his celebrated empirical laws of planetary motion, which gave further support to the Copernican system. But the real change in scientific opinion was brought about by Galileo Galilei (Figure 1.1), who was already famous for discovering the laws of falling bodies when he turned his attention to astronomy. Directing the newly invented telescope to the skies and applying his extraordinary gift for scientific observation to celestial phenomena, Galileo was able to discredit the old cosmology beyond any doubt and to establish the Copernican hypothesis as a valid scientific theory.

1.1.1 Galileo: mathematical description of nature

The role of Galileo in the Scientific Revolution goes far beyond his achievements in astronomy, although these are most widely known because of his clash with the Church. After Leonardo da Vinci, Galileo was the first to combine scientific experimentation with the use of mathematical language, and is therefore generally considered the father of modern science.

To make it possible for scientists to describe nature mathematically, Galileo postulated, as we have mentioned, that they should restrict themselves to studying only those properties of material bodies – shapes, numbers, and movement – that can be measured and quantified. Other properties, like color, taste, or smell, are merely subjective and should be excluded from the domain of science. In the centuries after Galileo this became a very successful strategy throughout modern science, but we also had to pay a heavy price. As the psychiatrist R.D. Laing (quoted by Capra, 1988, p. 133) put it emphatically,

> Galileo's program offers us a dead world: Out go sight, sound, taste, touch, and smell, and along with them have since gone esthetic and ethical sensibility, values, quality, soul, consciousness, spirit. Experience as such is cast out of the realm of scientific discourse. Hardly anything has changed our world more during the past four hundred years than Galileo's audacious program. We had to destroy the world in theory before we could destroy it in practice.

1.1.2 Bacon: domination of nature

Galileo's empirical approach was formalized and advocated with great vigor by his contemporary Francis Bacon (Figure 1.2), who boldly attacked traditional schools of thought and developed a veritable passion for scientific experimentation. The "Baconian spirit," as it was called, profoundly changed the nature and purpose of the scientific quest. From the time of the ancients, the goals of natural philosophy had been wisdom, understanding the natural order, and living in harmony with it. Science was pursued "for the glory of God." In the seventeenth century, this attitude changed dramatically.

As the organic view of nature was replaced by the metaphor of the world as a machine, the goal of science became knowledge that can be used to dominate and control nature.

The ancient concept of the Earth as nurturing mother was radically transformed in Bacon's writings, and it disappeared completely as the Scientific Revolution proceeded to replace the organic view of nature with the metaphor of the world as a machine. This shift, which was to become of overwhelming importance for the further development of Western civilization, was initiated and completed by two towering figures of the seventeenth century, Descartes and Newton.

Figure 1.2 Francis Bacon (1596–1650). iStockphoto.com/© Georgios Kollidas.

1.1.3 Descartes: the mechanistic view of the world

René Descartes (Figure 1.3) was not only the first modern philosopher but also a brilliant mathematician and scientist, whose philosophical outlook was profoundly affected by the new physics and astronomy. He did not accept any traditional knowledge but set out to build a whole new system of thought. According to the philosopher and mathematician Bertrand Russell (1961, p. 542), "This had not happened since Aristotle, and is a sign of the new self-confidence that resulted from the progress of science. There is a freshness about his work that is not to be found in any eminent previous philosopher since Plato."

Cartesian certainty

At the very core of Cartesian philosophy and of the worldview derived from it lies the belief in the certainty of scientific knowledge; and it was here, at the very outset, that Descartes went wrong. As we have discussed in the Introduction, twentieth-century science has shown very clearly that there can be no absolute scientific truth, that all our concepts and theories are necessarily limited and approximate.

Cartesian certainty is mathematical in its essential nature. Descartes believed that the key to the universe was its mathematical structure, and in his mind science was synonymous with mathematics. Like Galileo, Descartes believed that the language of nature was mathematics, and his desire to describe nature in mathematical terms led him to his most celebrated discovery. By applying numerical relations to geometrical figures, he was able

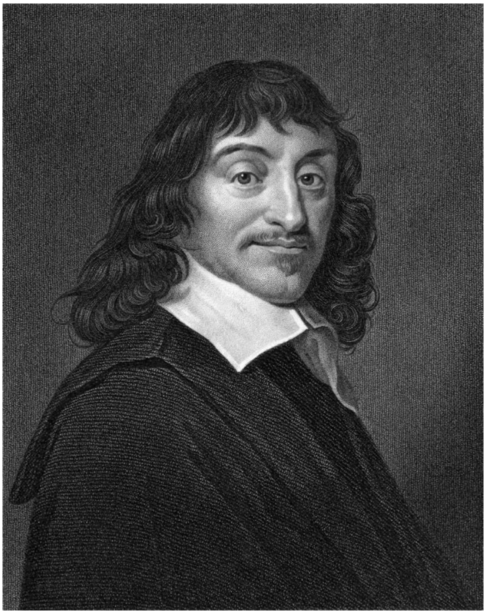

Figure 1.3 René Descartes (1596–1650). iStockphoto.com/© Georgios Kollidas.

to correlate algebra and geometry and, in doing so, founded a new branch of mathematics, now known as analytic geometry. This made it possible to represent geometrical curves by algebraic equations, whose solutions he studied in a systematic way. His new method allowed Descartes to apply a very general type of mathematical analysis to the study of moving bodies, in accordance with his grand scheme of reducing all physical phenomena to exact mathematical relationships. Thus he could say, with great pride, "My entire physics is nothing other than geometry" (quoted by Vrooman, 1970, p. 120).

Descartes' genius was that of a mathematician, and this is apparent also in his philosophy. To carry out his plan of building a complete and exact natural science, he developed a new method of reasoning which he presented in his most famous book, *Discourse on Method* (Descartes, 2006/1637). Although this text has become one of the great philosophical classics, its original purpose was not to teach philosophy but to serve as an introduction to science. Descartes' method was designed to reach scientific truth, as is evident from the book's full title, *A Discourse on the Method of Correctly Conducting One's Reason and Seeking Truth in the Sciences*.

The analytic method

The crux of Descartes' method is radical doubt. He doubts everything he can manage to doubt – all traditional knowledge, the impressions of his senses, and even the fact that he has a body – until he reaches one thing he cannot doubt, the existence of himself as a thinker. Thus he arrives at his celebrated statement, "*Cogito, ergo sum*" ("I think, and therefore I exist"). From this Descartes deduces that the essence of human nature lies in thought, and that all the things we conceive clearly and distinctly are true. Descartes' method is analytic. It consists in breaking up thoughts and problems into pieces and in arranging these in their logical order. This analytic method of reasoning is probably Descartes' greatest contribution to science. It has become an essential characteristic of modern scientific thought and has proven extremely useful in the development of scientific theories and the realization of complex technological projects. It was Descartes' method that made it possible for NASA to put a man on the Moon. On the other hand, overemphasis on the Cartesian method has led to the fragmentation that is characteristic of both our general thinking and our academic disciplines, and to the widespread attitude of reductionism in science – the belief that all aspects of complex phenomena can be understood by reducing them to their smallest constituent parts. (As we have discussed, no scientific description of natural phenomena can be completely accurate and exhaustive. In other words, all scientific theories are reductionist in the sense that they need to reduce the phenomena described to a manageable number of characteristics. However, science does not need not be reductionist in the Cartesian sense of reducing phenomena to their smallest constituents.)

Division between mind and matter

Descartes' *cogito*, as it has come to be called, made mind more certain for him than matter and led him to the conclusion that the two were separate and fundamentally different. The Cartesian division between mind and matter has had a profound effect on Western thought. It has taught us to be aware of ourselves as isolated egos existing "inside" our bodies; it has led us to set a higher value on mental than manual work; it has enabled huge industries to sell products – especially to women – that would make us owners of the "ideal body"; it has kept doctors from seriously considering the psychological dimensions of illness, and psychotherapists from dealing with their patients' bodies.

In the life sciences, the Cartesian division has led to endless confusion about the relation between mind and body, which has begun to be clarified only very recently by decisive advances in cognitive science (see Chapter 12). In physics, it has made it extremely difficult for the founders of quantum theory to interpret their observations of atomic phenomena (see Chapter 4). According to Werner Heisenberg (1958, p. 81), who struggled with the problem for many years, "This partition has penetrated deeply into the human mind during the three centuries following Descartes and it will take a long time for it to be replaced by a really different attitude toward the problem of reality."

Descartes based his whole view of nature on this fundamental division between two independent and separate realms; that of mind, or *res cogitans* (the "thinking thing"), and that of matter, or *res extensa* (the "extended thing"). Both mind and matter were creations of God, who represented their common point of reference, being the source of the exact natural order and of the light of reason that enabled the human mind to recognize this order. For Descartes, the existence of God was essential to his scientific philosophy, but in subsequent centuries scientists omitted any explicit reference to God while developing their theories according to the Cartesian division, the humanities concentrating on the *res cogitans* and the natural sciences on the *res extensa*.

Nature as a machine

To Descartes the material universe was a machine and nothing but a machine. There was no purpose, life, or spirituality in matter. Nature worked according to mechanical laws, and everything in the material world could be explained in terms of the arrangement and movement of its parts. This mechanical picture of nature became the dominant paradigm of science in the period following Descartes. It guided all scientific observation and the formulation of all theories of natural phenomena until twentieth-century physics brought about a radical change. The whole elaboration of mechanistic science in the seventeenth, eighteenth, and nineteenth centuries, including Newton's grand synthesis, was but the development of the Cartesian idea. Descartes gave scientific thought its general framework – the view of nature as a perfect machine, governed by exact mathematical laws.

The drastic change in the image of nature from organism to machine had a strong effect on people's attitudes toward the natural environment. The organic worldview of the Middle Ages had implied a value system conducive to ecologically minded behavior. In the words of Carolyn Merchant (1980, p. 3),

> The image of the earth as a living organism and nurturing mother served as a cultural constraint restricting the actions of human beings. One does not readily slay a mother, dig into her entrails for gold, or mutilate her body . . . As long as the earth was considered to be alive and sensitive, it could be considered a breach of human ethical behavior to carry out destructive acts against it.

These cultural constraints disappeared as the mechanization of science took place. The Cartesian view of the universe as a mechanical system provided a "scientific" sanction for the manipulation and exploitation of nature that became typical of modern civilization.

Descartes vigorously promoted his mechanistic view of the world in which all natural phenomena were reduced to the motions and mutual contacts of small material particles. The force of gravity, in particular, was explained by Descartes in terms of a series of impacts of tiny particles contained in subtle material fluids that permeated all space (see Bertoloni-Meli, 2006). This theory was highly influential throughout most of the seventeenth century, until Newton replaced it with his conception of gravity as a fundamental force of attraction between all matter.

Mechanistic view of living organisms

In his attempt to build a complete natural science, Descartes extended his mechanistic view of matter to living organisms. Plants and animals were considered simply machines; human beings were inhabited by a rational soul, but as far as the human body was concerned, it was indistinguishable from an animal-machine. Descartes explained at great length how the motions and various biological functions of the body could be reduced to mechanical operations, in order to show that living organisms were nothing but automata.

Descartes' view of living organisms had a decisive influence on the development of the life sciences. The careful description of the mechanisms that make up living organisms became the major task of biologists, physicians, and psychologists during the subsequent 300 years. The Cartesian approach has been very successful, especially in biology, but it has also limited the directions of scientific research. The problem has beeen that many scientists, encouraged by their success in treating living organisms as machines, tended to believe that they are *nothing but* machines. The adverse consequences of this reductionist fallacy have become especially apparent in medicine, where the adherence to the Cartesian model of the human body as a clockwork has prevented doctors from understanding many of today's major illnesses, as we discuss in Chapter 2.

Although the severe limitations of the Cartesian worldview have now become apparent in all the sciences, Descartes' general method of approaching intellectual problems and his clarity of thought remain immensely valuable. As the political philosopher Montesquieu (1689–1755) put it brilliantly, "Descartes has taught those who came after him how to discover his own errors" (quoted by Vrooman, 1970, p. 258).

1.1.4 Newton's synthesis

Descartes created the conceptual framework for seventeenth-century science, but his view of nature as a perfect machine, governed by exact mathematical laws, had to remain a vision during his lifetime. He could not do more than sketch the outlines of his theory of natural phenomena. The man who realized the Cartesian dream and completed the Scientific Revolution was Isaac Newton (Figure 1.4), born in England in the year of Galileo's death, 1642.

Newton developed a comprehensive mathematical formulation of the mechanistic view of nature, and thus accomplished a grand synthesis of the works of Copernicus and Kepler, Bacon, Galileo, and Descartes. Newtonian physics, the crowning achievement of seventeenth-century science, provided a consistent mathematical theory of the world that remained the solid foundation of scientific thought well into the twentieth century. Newton's grasp of mathematics was far more powerful than that of his contemporaries. He invented a completely new method, known today as differential calculus, to describe the motion of solid bodies; a method that went far beyond the mathematical techniques of Galileo and Descartes (as we discuss in more detail in Chapter 6). This tremendous intellectual achievement has been praised by Einstein (1931) as "perhaps the greatest advance in thought that a single individual was ever privileged to make."

Kepler had derived empirical laws of planetary motion by studying astronomical tables, and Galileo had performed ingenious experiments to discover the laws of falling bodies. Newton combined these two discoveries by formulating general laws of motion governing all objects in the solar system, from stones to planets. According to the well-known legend, the decisive insight occurred to Newton in a sudden flash of inspiration when he saw an apple fall from a tree. He realized that the apple was pulled toward the Earth by the same

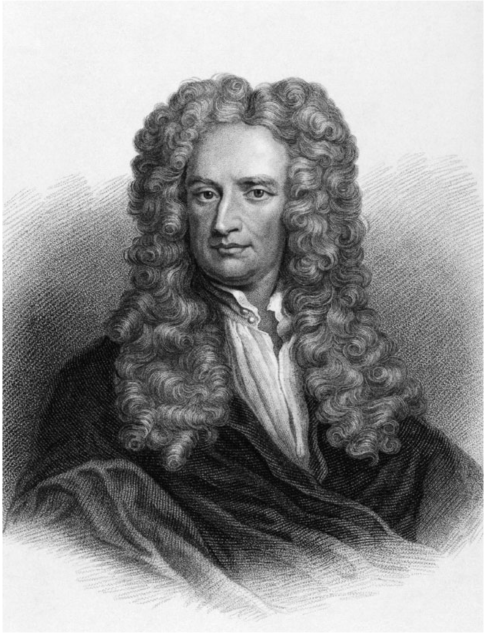

Figure 1.4 Isaac Newton (1642–1727). iStockphoto.com/© Georgios Kollidas.

force that pulled the planets toward the Sun, and thus found the key to his grand synthesis. He then used his new mathematical method to formulate the exact laws of motion for all bodies under the influence of the force of gravity. The significance of these laws lay in their universal application. They were found to be valid throughout the solar system and thus seemed to confirm the Cartesian view of nature. The Newtonian universe was, indeed, one huge mechanical system, operating according to exact mathematical laws.

The Principia

Newton (1999/1687) presented his theory of the world in his magnum opus, *Mathematical Principles of Natural Philosophy*. The *Principia*, as the work is usually called for short after its Latin title, comprises a comprehensive system of definitions, propositions, and proofs, which scientists regarded as the correct description of nature for more than 200 years. It also contains an explicit discussion of Newton's experimental method (quoted by Randall, 1976, p. 263), which he saw as a systematic procedure whereby the mathematical description is based, at every step, on critical evaluation of experimental evidence:

> Whatever is not deduced from the phenomena is to be called hypothesis, and hypotheses, whether metaphysical or physical, whether of occult qualities or mechanical, have no place in experimental philosophy. In this philosophy, particular propositions are inferred from the phenomena, and afterwards rendered general by induction.

Before Newton there had been two opposing trends in seventeenth-century science; the empirical, inductive method represented by Bacon and the rational, deductive method represented by Descartes. In the *Principia*, Newton introduced the proper mixture of both methods, emphasizing that neither experiments without systematic interpretation nor deduction from first principles without experimental evidence, will lead to a reliable theory. Going beyond Bacon in his systematic experimentation and beyond Descartes in his mathematical analysis, Newton unified the two trends and developed the methodology upon which natural science has been based ever since.

1.2 Newtonian physics

The stage of the Newtonian universe, on which all physical phenomena took place, was the three-dimensional space of classical Euclidean geometry. It was an absolute space, an empty container that was independent of the physical phenomena occurring in it. In Newton's own words (written in a special *Scholium on Absolute Space and Time*, attached to the *Principia*), "Absolute space, of its own nature, without reference to anything external, always remains homogeneous and immovable." All changes in the physical world were described in terms of a separate dimension, time, which again was absolute, having no connection with the material world and flowing smoothly from the past through the present to the future. "Absolute, true, and mathematical time," wrote Newton, "in and of itself and of its own nature, flows uniformly without reference to anything external."

The elements of the Newtonian world that moved in this absolute space and absolute time were material particles; small, solid, and indestructible objects out of which all matter was made. The Newtonian model of matter was atomistic, but it differed from the modern notion of atoms in that the Newtonian particles were all thought to be made of the same material substance. Newton assumed matter to be homogeneous. He explained the difference between one type of matter and another not in terms of atoms of different weights or densities but in terms of more or less dense packing of atoms. The basic building blocks of matter could be of different sizes but consisted of the same "stuff," and the total amount of material substance in an object was given by the object's mass.

The motion of the particles was caused by the force of gravity, which, in Newton's view, acted instantaneously over a distance. This conception was criticized by many of Newton's contemporaries, who were shocked by the idea that a force of attraction should act at a distance without being transmitted by any medium. The definitive solution of this vexing problem had to wait until the development of the field concept by Faraday and Maxwell in the nineteenth century (see Section 1.2.2) and of Einstein's theory of gravity in the twentieth (see Section 4.2.9).

For Newton, the material particles and the forces between them were indeed created by God and thus not subject to further analysis. In his second major scientific work, the *Opticks*, first published in 1704, Newton (1952/1730, Query 31) gave a clear picture of how he imagined God's creation of the material world:

> It seems probable to me that God in the beginning formed matter in solid, massy, hard, impenetrable, movable particles, of such sizes and figures, and with such other proportions, and in such proportion to space, as most conducted to the end for which he formed them; and that these primitive particles being solids, are incomparably harder than any porous bodies compounded of them; even so very hard, as never to wear or break in pieces; no ordinary power being able to divide what God himself made one in the first creation."

In Newtonian mechanics, all physical phenomena are reduced to the motion of these material particles, caused by their mutual attraction – that is, by the force of gravity. The effect of this force on a particle or any other material object is described mathematically by Newton's equations of motion. These were considered fixed laws according to which material objects moved, and were thought to account for all changes observed in the physical world. In the Newtonian view, God created in the beginning the material particles, the forces between them, and the fundamental laws of motion. In this way the whole universe was set in motion, and it has continued to run ever since, like a machine, governed by immutable laws. The mechanistic view of nature is thus closely related to a rigorous determinism, with the giant cosmic machine completely causal and determinate. All that happened had a definite cause and gave rise to a definite effect, and the future of any part of the system could – in principle – be predicted with absolute certainty if its state at any time was known in all details.

Even though the Newtonian worldview was based on laws that ultimately were of divine origin, the physical phenomena themselves were not thought to be divine in any sense. In subsequent centuries, science made it more and more difficult to believe in a creator God, and thus the divine disappeared completely from the scientific worldview, leaving behind a spiritual vacuum that became characteristic of the mainstream of modern culture.

The philosophical basis of this secularization of nature was the Cartesian division between mind and matter. As a consequence of this division, the world was believed to be a mechanical system that could be described objectively, without ever mentioning the human observer. In particular, human values were separated from scientific facts, and scientists henceforth tended to believe that scientific facts are independent of our values. Such an objective description of nature became the ideal of all science, an ideal that was maintained until the twentieth century when the fallacy of the belief in a value-free science was exposed, as we have discussed.

1.2.1 Success of Newtonian mechanics

In the eighteenth and nineteenth centuries, Newtonian mechanics was applied with tremendous success to a variety of phenomena. The Newtonian theory was able to explain the motion of the planets, moons, and comets down to the smallest details, as well as the flow of the tides and various other phenomena related to gravity. Newton's mathematical system of the world established itself quickly as the correct theory of reality and generated enormous enthusiasm among scientists and the lay public alike. The picture of the world as a perfect machine, which had been introduced by Descartes, was now considered a proven fact, and Newton became its symbol. During the last twenty years of his life, Sir Isaac Newton reigned in eighteenth-century London as the most famous man of his time, the great white-haired sage of the Scientific Revolution. Accounts of this period of Newton's life sound quite familiar to us because of our memories and photographs of Albert Einstein, who played a very similar role in the twentieth century.

Encouraged by the brilliant success of Newtonian mechanics in astronomy, physicists extended it to the continuous motion of fluids and the vibrations of elastic bodies, and again it worked. Finally, even the theory of heat could be reduced to mechanics when it was realized that heat was the energy generated by a complicated "jiggling" motion of atoms and molecules. Thus many thermal phenomena, such as the evaporation of a liquid, or the temperature and pressure of a gas, could be understood quite well from a purely mechanistic point of view.

The study of the physical behavior of gases led John Dalton (1766–1844) to the formulation of his celebrated atomic hypothesis, probably the most important step in the history of chemistry. Using Dalton's hypothesis, chemists of the nineteenth century developed a precise atomic theory of chemistry which paved the way for the conceptual unification of physics and chemistry in the twentieth century.

Thus Newtonian mechanics was extended far beyond the description of macroscopic bodies. The behaviors of solids, liquids, and gases, including the phenomena of heat and sound, were explained successfully in terms of the motion of elementary material particles. For the scientists of the eighteenth and nineteenth centuries this tremendous success of the mechanistic model confirmed their belief that the universe was indeed a huge mechanical system, running according to the Newtonian laws of motion, and that Newton's mechanics was the ultimate theory of natural phenomena.

With the firm establishment of the mechanistic worldview in the eighteenth century, physics naturally became the basis of all the sciences. Indeed, if the world is really a machine, the best way to find out how it works is to turn to Newtonian mechanics. It was thus an inevitable consequence of the Cartesian worldview that the sciences of the eighteenth and nineteenth centuries modeled themselves after physics. Descartes himself had sketched the outlines of a mechanistic approach to the life sciences (see Chapter 2). The thinkers of the eighteenth century carried this program further by applying the principles of Newtonian mechanics to the sciences of human nature and human society (see Chapter 3).

1.2.2 Limitations of the Newtonian model

As a result of extending the mechanistic approach to the life sciences and the social sciences, the Newtonian world-machine became a much more complex and subtle structure. At the same time, new discoveries and new ways of thinking made the limitations of the Newtonian model apparent and prepared the way for the scientific revolutions of the twentieth century.

Electromagnetism

One of these nineteenth-century developments was the discovery and investigation of electric and magnetic phenomena that involved a new type of force and could not be described appropriately by the mechanistic model. The important step was taken by Michael Faraday (1791–1867) and completed by James Clerk Maxwell (1831–1879) – the former one of the greatest experimenters in the history of science, the latter a brilliant theorist. Faraday and Maxwell not only studied the effects of the electric and magnetic forces but also made the forces themselves the primary objects of their investigation. By replacing the concept of a force with the much subtler concept of a field, they were the first to go beyond Newtonian physics, showing that fields had their own reality and could be studied without any reference to material bodies. This theory, called electrodynamics, culminated in the realization that light is in fact a rapidly alternating electromagnetic field traveling through space in the form of waves.

In spite of these far-reaching changes, Newtonian mechanics still held its position as the basis of all physics. Maxwell himself tried to explain his results in mechanical terms, interpreting the fields as states of mechanical stress in a very light, all-pervasive medium, called ether, and electromagnetic waves as elastic waves of this ether. However, he used several mechanical interpretations of his theory at the same time and apparently took none of them really seriously, knowing intuitively that the fundamental entities in his theory were the fields and not the mechanical models. It remained for Einstein to clearly recognize this fact in the twentieth century, when he declared that no ether existed, and that electromagnetic fields were physical entities in their own right, which could travel through empty space and could not be explained mechanically.

Evolutionary thought

While electromagnetism dethroned Newtonian mechanics as the ultimate theory of natural phenomena, a new trend of thinking arose that went beyond the image of the Newtonian world-machine – a trend that was to dominate not only the nineteenth century but also all future scientific thought. It involved the idea of evolution; of gradual change, growth, and development. The notion of evolution arose in geology, where careful studies of fossils led scientists to the idea that the present state of the Earth was the result of continuous development caused by the actions of natural forces over immense periods of time. But geologists were not the only ones who thought in those terms. The theory of the solar system proposed by Kant (1724–1804) and Laplace (1749–1827) was based on developmental, or evolutionary thinking; evolutionary concepts were crucial to the political philosophies of Hegel (1770–1831) and Engels (1820–1895); poets and philosophers alike, throughout the nineteenth century, were deeply concerned with the problem of becoming.

These ideas formed the intellectual background to the most precise and most far-reaching formulation of evolutionary thought – the theory of the evolution of species in biology. Ever since antiquity, natural philosophers had entertained the idea of a "great chain of being." This chain, however, was conceived as a static hierarchy, starting with God at the top and descending through angels, human beings, and animals to ever lower forms of life. The number of species was fixed; it had not changed since the day of their creation.

Lamarck and Darwin

The decisive change came with Jean-Baptiste Lamarck (1744–1829) at the beginning of the nineteenth century – a change that was so dramatic that Gregory Bateson (1972, p. 427), one of the deepest and broadest thinkers of the late twentieth century, compared it to the Copernican revolution:

> Lamarck, probably the greatest biologist in history, turned that ladder of explanation upside down. He was the man who said it starts with the infusoria and that there were changes leading up to man. His turning the taxonomy upside down is one of the most astonishing feats that has ever happened. It was the equivalent in biology of the Copernican revolution in astronomy.

Lamarck was the first to propose a coherent theory of evolution, according to which all living beings have evolved from earlier, simpler forms under pressure of their environment. Although the details of the Lamarckian theory had to be abandoned later on, it was nevertheless the first important step.

Several decades later, Charles Darwin (1809–1882) presented an overwhelming mass of evidence in favor of biological evolution, establishing the phenomenon for scientists beyond any doubt. He also proposed an explanation, based on the concepts of chance variation and natural selection that were to remain the cornerstones of modern evolutionary thought (as we discuss in detail in Chapter 9). Darwin's monumental *Origin of Species*, published in 1859, synthesized the ideas of previous thinkers and has shaped all subsequent biological thought. Its role in the life sciences was similar to that of Newton's *Principia* in physics two centuries earlier.

The discovery of evolution in biology forced scientists to abandon the Cartesian conception of the world as a machine that had emerged fully constructed from the hands of its creator. Instead, the universe had to be pictured as an evolving and ever-changing system in which complex structures developed from simpler forms. While this new way of thinking was elaborated in the life sciences, evolutionary concepts also emerged in physics. However, whereas in biology evolution meant a movement toward increasing order and complexity, in physics it came to mean just the opposite – a movement toward increasing disorder.

Thermodynamics

The application of Newtonian mechanics to the study of thermal phenomena, which involved treating liquids and gases as complicated mechanical systems, led physicists to the formulation of a new branch of science, thermodynamics. The first great achievement of this new science was the discovery of one of the most fundamental laws of physics, the law of the conservation of energy. It states that the total energy involved in a process is always conserved. It may change its form in the most complicated way – for example, from electrical energy to the energy of motion and energy of heat – but none of it is lost. This law, which physicists discovered in their study of steam engines and other heat-producing machines, is also known as the first law of thermodynamics.

It was followed by the second law of thermodynamics, that of the dissipation of energy. While the total energy involved in a process is always constant, the amount of useful energy is diminishing, dissipating into heat, friction, and so on. The second law was formulated first by Sadi Carnot (1796–1832) in terms of the technology of thermal engines, but was soon recognized to be of much broader significance. It introduced into physics the idea of irreversible processes, of an "arrow of time," as it came to be called. According to the second law, there is a certain trend in physical phenomena from order to disorder. Mechanical energy is always dissipated into heat that cannot be completely recovered. "You can scramble an egg," as physics teachers like to put it, "but you cannot unscramble it."

According to the second law, any isolated physical system will proceed spontaneously in the direction of ever-increasing disorder. To express this direction in the evolution of physical systems in precise mathematical form, physicists introduced a new quantity called "entropy," which measures the degree of disorder, and hence the degree of evolution of a physical system. According to classical thermodynamics, the entropy, or disorder, of the universe as a whole keeps increasing. The entire world-machine is running down and will eventually grind to a halt.

This grim picture of cosmic evolution is evidently in sharp contrast to the evolutionary idea held by biologists. At the end of the nineteenth century, the Newtonian image of the universe as a perfectly running machine had been supplemented by two diametrically opposed views of evolutionary change – that of a living world unfolding toward increasing order and complexity, and that of an engine running down, a world of ever-increasing disorder. Who was right, Darwin or Carnot?

It would take another hundred years to resolve the contradiction between the two theories of evolution developed in the nineteenth century (see Chapter 9). What would become clear is that the mechanistic conception of matter as a system of small billiard balls in random motion, which lies at the basis of thermodynamics, is far too simplistic to understand the evolution of life.

1.3 Concluding remarks

In this chapter we discussed the rise of Cartesian-Newtonian science during the Scientific Revolution, which would have a profound impact on Western culture during the subsequent 300 years. As we mentioned in the Introduction, there existed alternative, holistic views of reality during that era, those of the Renaissance and the Romantic movement being perhaps the most powerful ones. But the *Zeitgeist* of the Scientific Revolution defined the modern era for three centuries.

At the end of the nineteenth century, Newtonian mechanics had lost its role as the fundamental theory of natural phenomena. Maxwell's electrodynamics and Darwin's theory of evolution involved concepts that clearly went beyond the Newtonian model and indicated that the universe was far more complex than Descartes and Newton had imagined. Nevertheless, the basic ideas underlying Newtonian physics, though insufficient to explain all natural phenomena, were still believed to be correct. The first three decades of the twentieth century changed this situation radically, as we discuss in Chapter 4. Two new theories of physics, relativity theory and quantum theory, shattered all the principal concepts of the Cartesian worldview and Newtonian mechanics. The notion of absolute space and time, the elementary solid particles, the fundamental material substance, the strictly causal nature of physical phenomena, and the objective description of nature – none of these concepts could be extended to the new domains into which physics was advancing.

2

The mechanistic view of life

Descartes' uncompromising image of living organisms as mechanical systems established a clear conceptual framework for future research in biology, but he himself did not spend much time on physiological observations, leaving it to his followers to work out the details of the mechanistic view of life.

A comment on terminology is perhaps in order here. In this book we use the terms "Cartesian," "mechanistic," and "reductionist" interchangeably. All three terms refer to the scientific paradigm formulated by René Descartes in the seventeenth century (see Section 1.1.3), in which the material universe is seen as a machine and nothing but a machine.

In Descartes' mechanistic conception of the world, all of nature works according to mechanical laws, and everything in the material world can be explained in terms of the arrangement and movements of its parts. This implies that one should be able to understand all aspects of complex structures – plants, animals, or the human body – by reducing them to their smallest constituent parts. This philosophical position is known as Cartesian reductionism.

The fallacy of the reductionist view lies in the fact that, while there is nothing wrong in saying that the *structures* of all living organisms are composed of smaller parts, and ultimately of molecules, this does not imply that their *properties* can be explained in terms of molecules alone.

As we discuss in Section 4.3, the essential properties of a living system are emergent properties – properties that are not found in any of the parts but emerge at the level of the system as a whole. These emergent properties arise from specific patterns of organization – that is, from configurations of ordered relationships among the parts. This is the central insight of the systems view of life.

2.1 Early mechanical models of living organisms

In the seventeenth century, the first to be successful in applying the Cartesian approach was Giovanni Borelli (1608–1679), a student of Galileo, who managed to explain some basic aspects of muscle action in mechanistic terms. But the great triumph of seventeenth-century physiology came when William Harvey (1578–1657) applied the mechanistic model to the phenomenon of blood circulation and solved what had been the most fundamental and difficult problem in physiology since ancient times. Harvey's treatise *De motu cordis* ("On the Movement of the Heart"), published in 1628, gave a lucid description of all that could be known of the blood system in terms of anatomy and hydraulics without the aid of a microscope. It represented the crowning achievement of mechanistic physiology and was praised as such with great enthusiasm by Descartes himself.

Inspired by Harvey's success, the physiologists of his time tried to apply the mechanistic model to describe other bodily functions, such as digestion and tissue metabolism, but these attempts were dismal failures. The phenomena they tried to explain – often with the help of grotesque mechanical analogies – involve chemical and electromagnetic processes that were unknown at the time and could not be modeled in mechanical terms.

2.1.1 Cartesian reductionism

The situation changed considerably in the eighteenth century, which saw a series of important discoveries in chemistry, including the discovery of oxygen and the formulation of the modern theory of combustion by Antoine Lavoisier (1743–1794), the "father of modern chemistry." Lavoisier also demonstrated that respiration is a special form of oxidation and thus confirmed the relevance of chemical processes to the functioning of living organisms. At the end of the eighteenth century a further dimension was added to physiology when Luigi Galvani (1737–1798) demonstrated that the transmission of nerve impulses was associated with an electric current. This discovery led Alessandro Volta (1745–1827) to the study of electricity, which became the source of two new sciences, neurophysiology and electrodynamics.

These developments raised physiology to a new level of sophistication. The simplistic mechanical models of living organisms were abandoned, but the essence of the Cartesian idea survived. Animals were still machines, although they were much more complicated than mechanical clockworks, as they involved chemical and electrical phenomena. Thus biology ceased to be Cartesian in the sense of Descartes' strictly mechanical image of living organisms, but it remained Cartesian in the wider sense of attempting to reduce all aspects of living organisms to the physical and chemical interactions of their smallest constituents.

2.2 From cells to molecules

In the nineteenth century, the mechanistic view of life progressed further, due to remarkable advances in many areas of biology, including the formulation of cell theory, the beginning of modern embryology, the rise of microbiology, and the discovery of the laws of heredity. Biology was now firmly grounded in physics and chemistry, and scientists devoted all their efforts to the search for physical and chemical explanations of life.