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The Systems View of Life

A Unifying Vision

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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that most people in our modern society, and especially our large social institutions, subscribe to the concepts of an outdated worldview, a perception of reality inadequate for dealing with our overpopulated, globally interconnected world.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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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 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.

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.

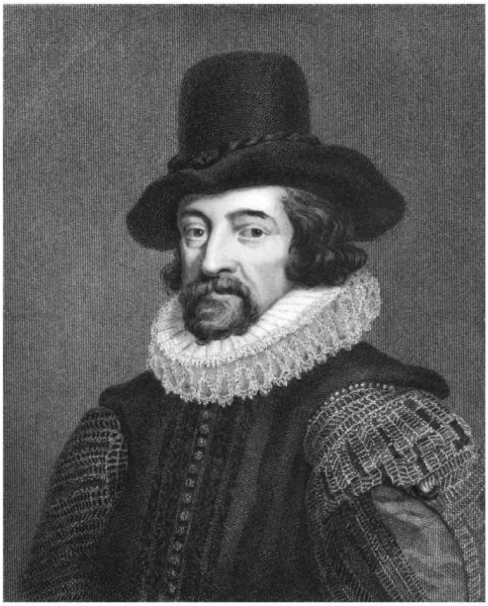

Figure 1.2 Francis Bacon (1596–1650). iStockphoto.com/© Georgios Kollidas.

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

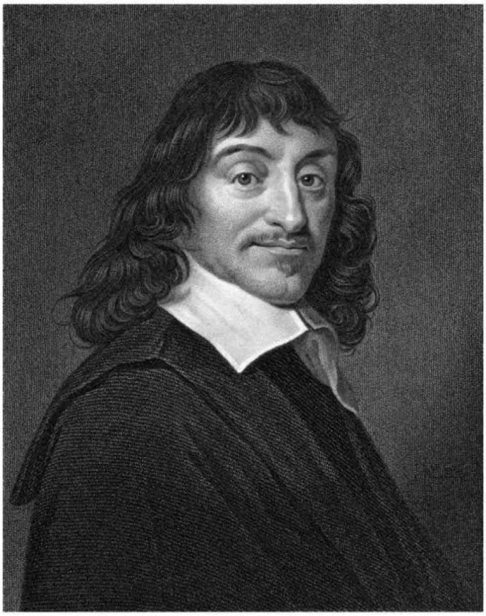

Figure 1.3 René Descartes (1596–1650). iStockphoto.com/© Georgios Kollidas.

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

> 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 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.

2.2.1 Cell theory

One of the most powerful generalizations in all of biology was the recognition that all animals and plants are composed of cells. It marked a decisive turn in biologists' understanding of body structure, inheritance, development, evolution, and many other characteristics of life. The term "cell" was coined by the physicist and naturalist Robert Hooke in the seventeenth century to describe various minute structures he saw through the newly invented microscope, but the development of a proper cell theory was a slow and gradual process that involved the work of many researchers and culminated in the nineteenth century with the formulation of modern cell theory by Robert Virchow (1821–1902). This achievement gave a new meaning to the Cartesian paradigm. Biologists thought that they had definitely found the fundamental units of life. From now on, all functions of living organisms had to be understood in terms of the interactions between cellular building blocks, rather than as reflecting the organization of the organism as a whole.

Understanding the structure and functioning of cells involves a problem that has become characteristic of all modern biology. The organization of a cell has often been compared to that of a factory, where different parts are manufactured at different sites, stored in intermediate facilities, and transported to assembly plants to be combined into finished products, which are either used by the cell itself or exported to other cells. Cell biology has made enormous progress in understanding the structures and functions of many of the cell's subunits, but it still has revealed very little about the coordinating activities that integrate those operations into the functioning of the cell as a whole. Biologists have come to realize that cells are living systems in their own right, and that the integrating activities of these living systems – especially the balancing of their interdependent metabolic pathways and cycles – cannot be understood within a reductionist framework.

2.2.2 Microbiology

The invention of the microscope in the seventeenth century had opened up a new dimension for biology, but the instrument was not fully exploited until the nineteenth century, when various technical problems with the old lens system were finally solved. The newly perfected microscope generated an entire new field of research, microbiology, which revealed an unsuspected richness and complexity of living organisms of microscopic dimensions. Research in this field was pioneered by the genius of Louis Pasteur (1822–1895), whose penetrating insights and clear formulations made a lasting impact on chemistry, biology, and medicine.

With the use of ingenious experimental techniques, Pasteur was able to clarify a question that had agitated biologists throughout the eighteenth century, the question of the origin of life. Since ancient times it had been a common belief that life, at least in its lower forms, could arise spontaneously from nonliving matter. During the seventeenth and eighteenth centuries that idea – known as "spontaneous generation" – was questioned, but the arguments could not be settled until Pasteur demonstrated conclusively that any microorganisms that developed under suitable conditions came from other microorganisms. It was Pasteur who brought to light the immense variety of the organic world at the level of the very small. In particular, he was able to establish the role of bacteria in chemical processes like fermentation, thus helping to lay the foundations of the new science of biochemistry.

After twenty years of research on bacteria, Pasteur turned to the study of diseases in higher animals and achieved another major advance – the demonstration of a definite correlation between "germs" (bacteria) and disease. Pasteur's discovery led to a simplistic "germ theory of disease," in which bacteria were seen as the only cause of disease. This reductionist view eclipsed an alternative theory that had been taught a few decades earlier by Claude Bernard (1813–1878), a celebrated physician who is generally considered the founder of modern physiology. Bernard insisted on the close and intimate relation between an organism and its environment, and was the first to point out that there was also a *milieu intérieur*, an internal environment in which the organs and tissues of the organism live. Bernard observed that in a healthy organism this internal environment remains essentially constant, even when the external environment fluctuates considerably. His concept of the constancy of the internal environment foreshadowed the important notion of homeostasis, developed by the neurologist Walter Cannon in the 1920s.

2.2.3 Darwin and Mendel

While the advances in cell theory and microbiology supported the mechanistic view of life, biology's main contribution to the history of ideas in the nineteenth century was Darwin's theory of evolution, which forced scientists to abandon the Newtonian image of the world as a machine that had remained unchanged since the time of its creation. As we discuss in detail in Chapter 9, Darwin's discovery that all forms of life have descended from a common ancestor by a long process of modifications over billions of years introduced a radical shift in biological thought – a change of perspective from being to becoming. Moreover, by realizing that all living organisms are related by common ancestry, the Darwinian conception of life was utterly holistic and systemic: a vast planetary network of living beings interlinked in space and time.

Although Darwin's twin concepts of chance variation – now known as random mutation – and natural selection would remain essential elements of modern evolutionary theory (as we discuss in Chapter 9), it soon became clear that chance variations, as envisaged by Darwin, could never explain the emergence of new characteristics in the evolution of species. Darwin shared with his contemporaries the assumption that the biological characteristics of an individual represented a "blend" of those of its parents, with both parents contributing more or less equal parts to the mixture. This meant that an offspring of a parent with a useful chance variation would inherit only 50% of the new characteristic, and would be able to pass on only 25% of it to the next generation. Thus the new characteristic would be diluted rapidly, with very little chance of establishing itself through natural selection. Darwin himself recognized that this was a serious flaw in his theory for which he had no remedy.

Ironically, the solution to Darwin's problem was discovered by the Austrian monk and scientist Gregor Mendel (1822–1884) only a few years after the publication of the Darwinian theory, but it was ignored until the rediscovery of Mendel's work at the turn of the twentieth century. From his careful experiments with garden peas (see Section 9.2), Mendel deduced that there were "units of heredity" – later to be called genes – that did not blend in the process of reproduction, but were transmitted from generation to generation without changing their identity. With this discovery it could be assumed that random mutations would not disappear within a few generations but would be preserved, to be either reinforced or eliminated by natural selection.

Mendel's discovery not only played a decisive role in establishing the Darwinian theory of evolution but also opened up a whole new field of research – the study of heredity through the investigation of the chemical and physical properties of genes. The biologist William Bateson (1861–1926), a fervent advocate and popularizer of Mendel's work, named this new field "genetics" at the beginning of the twentieth century and introduced many of the terms now used by geneticists. He also named his youngest son Gregory, in Mendel's honor.

2.3 The century of the gene

In the twentieth century, genetics became the most active area in biological research and provided a strong reinforcement of the Cartesian approach to living organisms. It became clear quite early on that the material of heredity lay in the chromosomes, those threadlike bodies that are present in the nucleus of every cell. Soon thereafter it was recognized that the genes occupy specific positions within the chromosomes; to be more precise, they are arranged along the chromosomes in linear order. With these discoveries geneticists believed that they had now pinned down the "atoms of heredity" and proceeded to explain the biological characteristics of living organisms in terms of their elementary units, the genes.

This new perspective brought about a significant shift in biological research – a shift that may well turn out to be the last step in the reductionist approach to the phenomenon of life, leading to its greatest triumph and, at the same time, to its demise. 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 when geneticists began to explore the molecular structure of the gene. Their research culminated in the elucidation of the physical structure of DNA – the genetic component of chromosomes – which stands as one of the greatest achievements of twentieth-century science. This triumph of molecular biology led biologists to believe that all biological functions can be explained in terms of molecular structures and mechanisms.

2.3.1 Genes and enzymes

During the first half of the twentieth century it became clear that the essential constituents of all living cells – the proteins and nucleic acids (DNA and RNA) – were highly complex, chainlike structures containing thousands of atoms. The investigation of the chemical properties and exact three-dimensional structure of these large-chain molecules became the principal task of molecular biology.

The first important step toward a molecular genetics came with the discovery that cells contain agents, called enzymes, that can catalyze (i.e., mediate) specific chemical reactions. During the first half of the twentieth century biochemists managed to specify most of the chemical reactions that occur in cells, and found out that the most important of these reactions are essentially the same in all living organisms. Each of them depends crucially on the presence of a specific enzyme, and thus the study of enzymes became of primary importance.

During the 1940s geneticists had another decisive insight when they discovered that the primary function of genes was to control the production, or "synthesis," of enzymes. With this discovery the broad outlines of the hereditary process emerged: genes determine hereditary traits by directing the synthesis of enzymes, which in turn mediate the chemical reactions corresponding to those traits.

Although these discoveries represented major advances in understanding heredity, the nature of the gene remained unknown during this period. Geneticists ignored its chemical structure and were unable to explain how it managed to carry out its essential functions: the synthesis of enzymes, its own faithful replication in the process of cell division, and the sudden permanent changes known as mutations. As far as the enzymes were concerned, it was known that they were proteins, but their precise chemical structure was unknown and so, as a consequence, was the process by which enzymes catalyze chemical reactions.

2.3.2 Schrödinger's **What Is Life?**

This situation changed radically over the next two decades, which brought the major breakthrough in modern genetics, often referred to as the breaking of the genetic code: the discovery of the precise chemical structure of genes and enzymes, of the molecular mechanisms of protein synthesis, and of the mechanisms of gene replication and mutation. A crucial element in the breaking of the genetic code was the fact that physicists moved into biology. Max Delbrück, Francis Crick, Maurice Wilkins, and several of the other protagonists had backgrounds in physics before they joined the biochemists and geneticists in their study of heredity. These scientists brought with them a new perspective and new methods that thoroughly transformed genetic research.

The main reason for these scientists to leave physics and turn to genetics was a short book entitled *What Is Life?*, published in 1944 by the famous quantum physicist Erwin Schrödinger (1887–1961). The fascination of Schrödinger's book came from the clear and compelling way in which he treated the gene not as an abstract unit but as a concrete physical substance, advancing definite hypotheses about its molecular structure that stimulated scientists to think about genetics in a new way. Schrödinger was the first to suggest that biology, leaving out all influences of nonbiological circumstances on biological processes. Out of the large network of phenomena that influence health, the biomedical approach studies only a few physiological aspects. Knowledge of these aspects is, of course, very useful, but they represent only a small part of the story. Medical practice based on such a limited approach is not very effective in promoting and maintaining good health. This will not change until medical science relates its study of the biological aspects of illness to the general physical and psychological condition of the human organism and its environment.

The conceptual problem at the center of contemporary healthcare is the confusion between disease processes and disease origins. Instead of asking why an illness occurs and trying to remove the conditions that led to it, medical researchers try to understand the mechanisms through which the disease operates, so that they can then interfere with them. These mechanisms, rather than the true origins, are seen as the causes of disease in current medical thinking.

In the process of reducing illness to disease, the attention of physicians has moved away from the patient as a whole person. By concentrating on smaller and smaller fragments of the body – shifting its perspective from the study of bodily organs and their functions to that of cells and, finally, to the study of molecules – modern medicine often loses sight of the human being, and having reduced health to mechanical functioning, it is no longer able to deal with the phenomenon of healing. Over the past four decades, the dissatisfaction with the mechanistic approach to health and healthcare has grown rapidly both among healthcare professionals and the general public. At the same time, the emerging systems view of life has given rise to a corresponding systems view of health, as we discuss in Chapter 15, while health consciousness among the general population has increased dramatically in many countries. The growing awareness of the power and the responsibility of individuals to maintain themselves in good health has expressed itself in increased attention to healthy nutrition, exercise, yoga and other "mind–body" practices, as well as in the rising popularity of a wide range of alternative therapies.

In the late 1970s and early 1980s, the leading catchphrases of this broad popular movement were "holistic healthcare," "holistic medicine," and "wellness," and in the subsequent decades the phrase "integrative medicine" established itself as the unifying term. We shall argue in Chapter 15 that, in our view, integrative medicine represents the conscientious application of the systems view of life to health and healing.

2.5 Concluding remarks

The spectacular success of molecular biology in the field of genetics – the discovery of the structure of DNA and the "breaking of the genetic code" – has been hailed as the greatest achievement in biology since Darwin's theory of evolution. Indeed, at the close of the twentieth century the biologist and science historian Evelyn Fox Keller wrote a review of genetics titled *The Century of the Gene*. However, Keller gave this phrase a double meaning. The main point of her brilliant evaluation of genetics is the observation that the most recent advances in this field are now forcing molecular biologists to question many of the fundamental concepts on which their whole enterprise was originally based. Thus Keller comes to the conclusion:

> Even though the message has yet to reach the popular press, to an increasingly large number of workers at the forefront of contemporary research, it seems evident that the primacy of the gene as the core explanatory concept of biological structure and function is more a feature of the twentieth century than it will be of the twenty-first.
>
> (*Keller, 2000, p. 9*)

3

Mechanistic social thought

3.1 Birth of the social sciences

While Descartes himself has sketched the outlines of a mechanistic approach to physics, biology, and medicine, the thinkers of the eighteenth century carried this program further by applying the principles of Newtonian mechanics to the study of human nature and human society. In doing so, they created a new branch of science, which they called "social science" (later changed to the plural "social sciences" to denote a variety of disciplines outside the natural sciences). This new science generated great enthusiasm, and some of its proponents even claimed to have discovered a "social physics."

The Newtonian theory of the universe and the belief in the rational approach to human problems spread so rapidly among the middle classes of the eighteenth century that the whole era became known as the "Age of Enlightenment," or the "Age of Reason." The dominant figure in this development was the philosopher John Locke (Figure 3.1), whose most important writings were published in the late seventeenth century. Strongly influenced by Descartes and Newton, Locke's work had a decisive impact on eighteenth-century thought.

3.1.1 The Enlightenment

Following Newtonian physics, Locke developed an atomistic view of society, describing it in terms of its basic building blocks, the individual human beings. As physicists reduced the properties of gases to the motion of their atoms, or molecules, so Locke attempted to reduce the phenomena observed in society to the behavior of its individuals. Thus he proceeded to study first the nature of the individual human being, and then tried to apply the principles of human nature to economic and political problems.

Locke's analysis of human nature was based on that of an earlier philosopher, Thomas Hobbes (1588–1679), who had declared that all knowledge was based on sensory perception. Locke adopted this theory of knowledge and, in a famous metaphor, compared the human mind at birth to a *tabula rasa*, a completely blank tablet on which knowledge is imprinted once it is acquired through sensory experience. This image was to have a strong influence on psychology as well as on political philosophy. According to Locke, all human

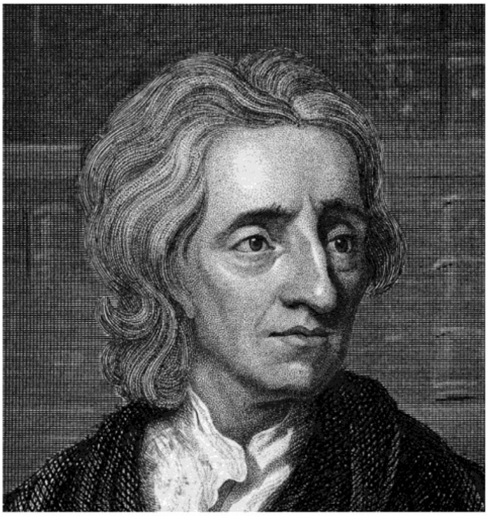

Figure 3.1 John Locke (1632–1727). iStockphoto.com/© pictore.

beings – “all men,” as he would say – were equal at birth and depended in their development entirely on their environment. Their actions, Locke believed, were always motivated by what they assumed to be in their own interest.

When Locke applied his theory of human nature to social phenomena, he was guided by the belief that there were laws of nature governing human society similar to those governing the physical universe. As the atoms in a gas would establish a balanced state, so human individuals would settle down in society in a “state of nature.” Thus the function of government was not to impose its own laws on the people, but rather to discover and enforce the natural laws that existed before any government was formed. According to Locke, these natural laws included the freedom and equality of all individuals as well as the right to property, which represented the fruits of one’s labor.

Locke’s ideas became the basis for the value system of the Enlightenment and had a strong influence on the development of modern economic and political thought. The ideals of individualism, property rights, free markets, and representative government, all of which can be traced back to Locke, contributed significantly to the thinking of Thomas Jefferson and are reflected in the Declaration of Independence and the American Constitution.

3.1.2 The positivist straitjacket

Social thought in the late nineteenth and early twentieth centuries was greatly influenced by positivism, a doctrine formulated by the social philosopher Auguste Comte (1798–1857). Its assertions include the insistence that the social sciences should search for general laws of human behavior, an emphasis on quantification, and the rejection of explanations in terms of subjective phenomena, such as intentions or purposes.

It is evident that the positivist framework is patterned after Newtonian physics. Indeed, it was Auguste Comte who called the scientific study of society at first "social physics" before introducing the term "sociology." The major schools of thought in early twentieth-century sociology can be seen as attempts at emancipation from the positivist straitjacket. In fact, as Baert (1998) shows in a concise review of twentieth-century social theory, most sociologists of that time positioned themselves explicitly in opposition to the positivist epistemology.

3.1.3 "Hard" and "soft" sciences

The triumph of Newtonian mechanics in the eighteenth and nineteenth centuries established physics as the prototype of a "hard" science against which all other sciences were measured. The closer scientists could come to emulating the methods of physics, and the more of its concepts they were able to use, the higher the standing of their discipline in the scientific community.

In the twentieth century, this tendency to model scientific concepts and theories after those of Newtonian physics became a severe handicap in many fields, but first and foremost in the social sciences. These were traditionally regarded as the "softest" among the sciences, and social scientists tried very hard to gain respectability by adopting the Cartesian paradigm and the methods of Newtonian physics. However, the Cartesian framework is often quite inappropriate for the phenomena they are describing, and consequently their models have become increasingly unrealistic. This is now especially apparent in economics. Our brief review of the history of economics in the following pages is based on an essay written by the economist and futurist Hazel Henderson (see Capra, 1982; see also Henderson, 1978, 1981).

3.1.4 The emergence of economics

Economic theory emerged with the Scientific Revolution and the Enlightenment, and found its classical formulation during the Industrial Revolution. Before the sixteenth century there was no isolation of purely economic phenomena from the fabric of life. Throughout most of human history food, clothing, shelter, and other basic resources were produced for use value and were distributed within tribes and groups on a reciprocal basis (see Polanyi, 1968). A national system of markets is a relatively recent phenomenon that arose in seventeenth-century England and spread from there over the entire world, resulting in today's interlinked "global market." Markets, of course, had existed since the Stone Age, but they were based on barter, not cash, and thus were bound to be local. Even early trading had little economic motivation but was more often a sacred and ceremonial activity related to kinship and family customs.

With the Scientific Revolution and the Enlightenment, critical reasoning, empiricism, and individualism became the dominant values, together with a secular and materialistic orientation that led to the production of worldly goods and luxuries, and to the manipulative foundation of modern economic theory has been compared to that of Newton's *Principia* for physics and of Darwin's *Origin of Species* for biology.

Smith lived at a time when the Industrial Revolution had begun to change the face of Britain. When he wrote *The Wealth of Nations* the transition from an agrarian, handicraft economy to one dominated by steam power and by machines operated in large factories and mills was well under way. The spinning jenny had been invented and machine looms were used in cotton factories employing up to 300 workers. The new private enterprise, factories, and power-driven machinery shaped Smith's ideas to such an extent that he enthusiastically advocated the social transformation of his time and criticized the remnants of the land-based feudal system.

From the prevailing Newtonian idea of natural law Smith deduced that it was "human nature to barter and exchange," and he also thought it "natural" that workers would gradually facilitate their work and improve their productivity with the help of labor-saving machinery. At the same time the early manufacturers had a much darker view of the role of machines; they well understood that machines could replace workers and thus could be used to keep them afraid and docile.

3.2.2 The invisible hand

From the Physiocrats Smith adopted the theme of laissez faire, which he immortalized in the metaphor of the "invisible hand". According to Smith, the invisible hand of the market would guide the individual self-interest of all entrepreneurs, producers, and consumers for the harmonious betterment of all, "betterment" being equated with the production of material wealth. In this way a social result would be achieved that was independent of individual intentions, and thus an objective science of economic activity was made possible.

Smith believed in the labor theory of value, according to which the value of a product is derived only from the human labor required to produce it, but he also accepted the idea that prices would be determined in "free" markets by the balancing effects of supply and demand. He based his economic theory on the Newtonian notions of equilibrium, laws of motion, and scientific objectivity. One of the difficulties in applying these mechanistic concepts to social phenomena was the lack of appreciation for the problem of friction. Because the phenomenon of friction is generally neglected in Newtonian mechanics, Smith imagined that the balancing mechanisms of the market would be almost instantaneous. He described their adjustments as "prompt," "occurring soon," and "continual," while prices were "gravitating" in the proper direction. Small producers and small consumers would meet in the marketplace with equal power and information.

This idealistic picture underlies the "competitive model" widely used by economists today. Its basic assumptions include perfect and free information for all participants in a market transaction; the belief that each buyer and seller in a market is small and has no influence on price; and the complete and instant mobility of displaced workers, natural resources, and machinery. All these conditions are violated in the vast majority of today's markets, yet most economists continue to use them as the basis of their theories.

Smith thought that the self-balancing market system was one of slow and steady growth, with continually increasing demands for goods and labor. This idea of continual growth was adopted by succeeding generations of economists, who, paradoxically continued to use mechanistic equilibrium assumptions while at the same time postulating continuing economic growth. Smith himself predicted that economic progress would eventually come to an end when the wealth of nations had been pushed to the natural limits of soil and climate, but he thought this point was so far in the future that it was irrelevant to his theories. Today our global economy is fast approaching these natural limits, as we discuss in Chapter 17.

Smith alluded to social and economic structures like monopolies when he denounced people in the same trade who conspired to raise prices artificially, but he did not see the broad implications of such practices. The growth of these structures, and in particular of the class structure, was to become a central theme in Marx's economic analysis. Adam Smith justified capitalists' profits by arguing that they were needed to invest in more machines and factories for the common good. He noted the struggle between workers and employers and the efforts of both to "interfere with the market," but he never referred to the unequal power of workers and capitalists – a point that Marx would drive home with force.

3.2.3 Economic models

At the beginning of the nineteenth century, economists began to systematize their discipline in an attempt to cast it into the form of a science. The first and most influential among these systematic economic thinkers was David Ricardo (1772–1823), who introduced the concept of an "economic model," a logical system of postulates and laws, involving a limited number of variables that could be used to describe and predict economic phenomena.

The systematic efforts of Ricardo and other classical economists consolidated economics into a set of dogmas that supported the existing class structure and countered all attempts at social improvement with the "scientific" argument that "laws of nature" were operating and the poor were responsible for their own misfortune. At the same time, workers' uprisings were becoming frequent and the new body of economic thought engendered its own horrified critics long before Marx.

3.3 The critics of classical economics

3.3.1 John Stuart Mill

The greatest among the classical economic reformers was John Stuart Mill (1806–1873), a child prodigy who had absorbed most of the works of the philosophers and economists of his time by the time he was thirteen. At the age of forty-two he published his own *Principles of Political Economy*, a herculean reassessment that came to a radical conclusion. Economics,

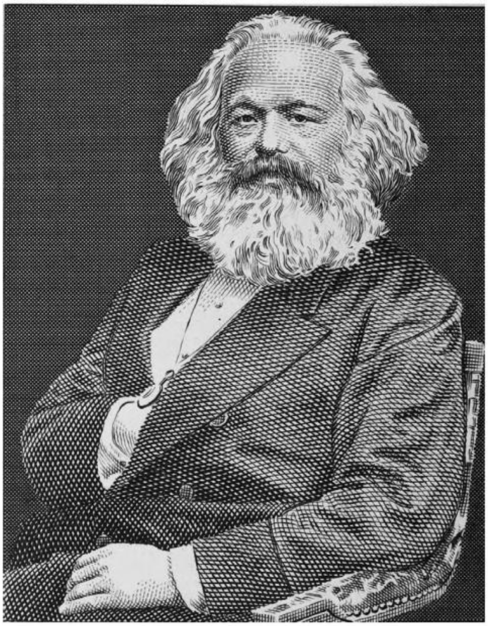

Figure 3.3 Karl Marx (1818–1883). iStockphoto.com/© Rubén Hidalgo.

Mill wrote, had only one province: production and the scarcity of means. Distribution was not an economic but a political process. This narrowed the scope of political economy to "pure economics," later to be called "neoclassical," and allowed a more detailed focus on the "economic core process," while excluding social and environmental variables in analogy to the controlled experiments of the physical sciences.

After Mill, economics became split between the neoclassical, "scientific," and mathematical approach, on the one hand, and the "art" of broader social philosophy on the other. Eventually this split led to today's disastrous confusion between the two approaches, resulting in policy tools that are often derived from abstract, unrealistic mathematical models.

3.3.2 Karl Marx

The thought of Karl Marx (Figure 3.3), the most thorough and most eloquent critic of classical economics, has engendered worldwide intellectual fascination far beyond the field of economics. According to economic historian Robert Heilbroner (1978), this fascination is rooted in the fact that Marx was "the first to discover a whole mode of inquiring that would forever after belong to him." Marx's mode of inquiry was that of social critique. He referred to himself not as a philosopher, historian, or economist – though he was all of those – but as a social critic; and this is why his social philosophy and science continue to exert a strong influence on social thought.

As a philosopher, Marx taught a philosophy of action. "The philosophers," he wrote, "have only *interpreted* the world in various ways; the point, however, is to *change* it" (quoted in Tucker, 1972, p. 109). As an economist, Marx criticized classical economics more expertly and efficiently than any of its practitioners. His main influence, however, has been not intellectual but political. As Heilbroner (1980, p. 134) observed, if judged by the number of worshiping followers, "Marx must be considered a religious leader to rank with Christ or Mohammed."

While Marx the revolutionary was canonized by millions around the world, economists had to deal with – but more often ignored or misquoted – his embarrassingly accurate predictions, among them the occurrence of "boom" and "bust" business cycles and the tendency of market-oriented economies to develop "reserve armies" of unemployed.

Marx's main body of work, set forth in his three-volume *Das Kapital* ("Capital"), represents a thorough critique of capitalism. He viewed society and economics from the explicitly stated perspective of the struggle between workers and capitalists, but his broad ideas about social evolution allowed him to see economic processes in much larger contexts.

Marx recognized that capitalist forms of social organization would speed the process of technological innovation and increase material productivity, and he predicted that this, "dialectically" (i.e., by changing into its opposite), would change social relationships. Thus he was able to foresee phenomena like monopolies and depressions, and to predict that capitalism would foster socialism – as it did – and that it would, eventually, disappear – as it may.

In his "Critique of Political Economy," as he subtitled *Das Kapital*, Marx used the labor theory of value to raise issues of justice, and developed powerful new concepts to counter the reductionist logic of the neoclassical economists of his time. He knew that to a large extent wages and prices are politically determined. Starting from the premise that human labor creates all values, Marx observed that continuing labor must, at the very least, produce subsistence for the worker plus enough to replace the materials used up. But, in general, there will be a surplus over and above that minimum. The form this "surplus value" takes will be a key to the structure of society, its economy, and its technology.

In capitalist societies, Marx pointed out, the surplus value is appropriated by capitalists, who own the means of production and determine the conditions of labor. This transaction between people of unequal power allows the capitalists to make more money from the labor of the workers, and thus money is turned into capital. In this analysis Marx emphasized that the precondition for capital to arise was a specific social class relationship, itself the product of a long history.

Marx had a rich intellectual life with many insights that have decisively shaped our age. His social critique inspired millions of revolutionaries around the world, and the Marxian economic analysis, although now somewhat outdated (as we discuss in Chapter 17), is respected academically not only in former and current socialist countries but also in most other countries around the world. Even in the USA, Marxian thought is taught, with different emphases, in all leading universities, and some of the most prominent American social scientists – e.g., Michael Burawoy at Berkeley, David Harvey at City College of New

York, or Erik Olin Wright at Wisconsin – are known explicitly as Marxian scholars. In fact, it is interesting that from the 1970s on, Marxism has been growing among American academics while it has almost disappeared in France and other European countries, let alone Russia.

As the work of the scholars mentioned shows, Marxian thought is capable of a wide range of interpretations and thus continues to fascinate. Of particular interest for our review is the relation of the Marxian critique to the reductionist framework of the science of his time. Like most nineteenth-century thinkers, Marx was very concerned about being "scientific," using the term constantly in the description of his critical approach. Accordingly he often attempted to formulate his theories in Cartesian and Newtonian language. Still, his broad view of social phenomena allowed him to transcend the Cartesian framework in significant ways.

He did not adopt the classical stance of the objective observer, but fervently emphasized his role as participator by asserting that his social analysis was inseparable from social critique. In his critique he went beyond social issues and often revealed deeply humanistic insights. Finally, although Marx often argued for technological determinism (i.e., the belief that technological development determines social change), a fact which made his theory more acceptable as a science, he also had profound insights into the interrelatedness of all phenomena, seeing society as an organic whole in which ideology and technology are equally important.

3.4 Keynesian economics

3.4.1 Neoclassical models and the Great Depression

By the middle of the nineteenth century, classical political economy had branched into two broad streams. On the one side were the reformers: the Marxists and the minority of classical economists who followed John Stuart Mill. On the other side were the neoclassical economists, who concentrated on the economic core process and developed the school of mathematical economics. Some of them tried to establish objective formulas for the maximization of welfare, while others retreated into ever more abstruse mathematics to escape the devastating Marxist critique.

Much of mathematical economics was – and is – devoted to studying the "market mechanism" with the help of curves for demand and supply, always expressed as functions of prices and based on various assumptions about economic behavior, many of them highly unrealistic in today's world. For example, perfect competition in free markets, as postulated by Adam Smith, is assumed in many models.

As mathematical economists refined their models during the late nineteenth and early twentieth centuries, the world economy headed for the worst depression in its history, which shook the foundations of capitalism and seemed to verify all the Marxian predictions. However, after the Great Depression capitalism's fortunes were saved by a new set of social and economic interventions of governments. These policies were based on the theory of

3.5.3 Economics in crisis

The fragmentary approach of contemporary economists, their preference for abstract quantitative models, and their inability to see economic activities within their proper ecological context have resulted in a tremendous gap between theory and economic reality. As a consequence, economics today is in a profound conceptual crisis. This became strikingly apparent during the global financial crisis of 2008–9.

As the CBS journalist Steve Kroft (2008) showed in detail, the crisis was brought about by Wall Street bankers through a combination of greed, incompetence, and weaknesses inherent in the system. It began as a mortgage crisis, caused by the reckless marketing of risky "subprime" loans; then it slowly evolved into a credit crisis; and finally it became a global financial crisis. During the mortgage crisis, big Wall Street investment houses bought up millions of the least dependable mortgages, chopped them up into tiny bits and pieces, and repackaged them as exotic investment securities that hardly anyone could understand. For this repackaging they collected enormous fees.

These complex financial instruments which lay at the heart of the credit crisis were actually designed by mathematicians and physicists, who used computer models to reconstitute the unreliable loans in ways that were supposed to eliminate most of the risks. But their models turned out to be wrong, because physicists and mathematicians are not experts in human behavior, and human behavior cannot be modeled mathematically. In their misguided efforts, they followed a long tradition of economists modeling how consumers behave as rational actors and self-interested individuals, competing with each other to maximize their own gain. These narrow models, in which pure greed is the main ingredient, are mere caricatures of actual human behavior, and hence their failure is not surprising.

In the wake of the global financial crisis, two economics professors, Kamran Mofid and Steve Szeghi (2010), wrote a very sober, reflective essay, titled "Economics in Crisis: What Do We Tell the Students?" They argued that the standard economic theory being taught at our major universities may have been responsible not only for the striking failure to predict the timing and magnitude of the events that unfolded in 2008 but also even for the crisis itself. Their analysis led the authors to a stark conclusion:

> Now is the time to acknowledge the failures of standard theory and the narrowness of market fundamentalism. The times demand a revolution in economic thought, as well as new ways of teaching economics. In many respects this means a return to the soil in which economics was initially born, moral philosophy amid issues and questions of broad significance involving the fullness of human existence.

3.6 The machine metaphor in management

3.6.1 The mechanization of human organizations

In the centuries after Descartes and Newton, the view of the world as a mechanical system composed of elementary building blocks shaped people's perceptions not only of nature, the human organism, and society but also of the human organizations within society. As the metaphor of organizations as machines took hold, it generated corresponding mechanistic theories of management with the aim of increasing an organization's efficiency by designing it as an assemblage of precisely interlocking parts – functional departments such as production, marketing, finance, and personnel – linked together through clearly defined lines of command and communication.

As Morgan (1998) explains in his detailed review of mechanistic management theories, the machine metaphor became prominent during the Industrial Revolution when factory owners and their engineers realized that the efficient operation of the new machines required major changes in the organization of the workforce. With increasing specialization of manufacturing, the division of labor intensified, control of the machines was shifted from workers to their supervisors, and new procedures were introduced to discipline workers and force them to accept the rigorous routines of factory production.

As Morgan (1998) puts it, "Organizations that used machines became more and more like machines."

3.6.2 Classical management theories

During the nineteenth century, various attempts were made to represent and promote the new mechanistic view of human organizations in a systematic way, but it was only in the early twentieth century that coherent theories of organization and management were developed. One of the first organizational theorists was the influential social scientist Max Weber (1864–1920), whose theory about the origin of capitalism we discussed in Section 3.1.4. A keen observer of social and political phenomena, Weber emphasized the role of values and ideologies in shaping societies. Accordingly, he was very critical of the development of mechanistic forms of organization in parallel to that of actual machines.

Weber was not only one of the first observers of the parallels between the mechanization of industry and bureaucratic forms of organization, but also the first to offer a comprehensive definition of bureaucracy as a form of organization emphasizing precision, clarity, regularity, reliability, and efficiency. He was concerned about the psychological and social effects of the proliferation of bureaucracy – the mechanization of human life, the erosion of the human spirit, and the undermining of democracy.

Subsequent management theorists, by contrast, were firm advocates of bureaucratization. They identified and promoted detailed principles and methods through which organizations could be made to function with machine-like efficiency. These theories became known as "classical management theories" and "scientific management."

Frederick Taylor (1911), in particular, perfected the engineering approach to management in his *Principles of Scientific Management*. Taylor's principles, known today as Taylorism, provided the cornerstone of management theory during the first half of the twentieth century. As Morgan (1998, pp. 27–8) points out, Taylorism in its original form is still alive in numerous fast-food chains around the world. In these mechanized restaurants that serve hamburgers, pizzas, and other highly standardized products, “work is often organized in the minutest detail on the basis of designs that analyze the total process of production, find the most efficient procedures, and then allocate these as specialized duties to people trained to perform them in a very precise way. All the thinking is done by the managers and designers, leaving all the doing to the employees.”

3.6.3 The machine metaphor today

In the second half of the twentieth century, the machine metaphor continued to have a profound impact on the theory and practice of management, and it was only during the last two decades that organizational theorists began to apply the systems view of life to the management of human organizations (as we discuss in Chapter 14). Even today, however, the mechanistic view of organizations is still widespread among managers.

A company, in this view, is created and owned by people outside the system. Its structure and goals are designed by management or by outside experts and are imposed on the organization. As a machine must be controlled by its operators to function according to their instructions, so the main thrust of management theory has been to achieve efficient operations through top-down control.

Seeing a company as a machine implies that it will eventually run down, unless it is periodically “serviced” and rebuilt by management. It cannot change by itself; all changes need to be designed by someone else. In the 1990s, a new mechanistic catch phrase – “re-engineering” – was invented to describe such redesign of human organizations. It sparked a whole movement dedicated to shift the focus from bureaucratic functions to key business processes.

The principles of classical management theory have become so deeply ingrained in the ways managers think about organizations that for most of them the design of formal structures, linked by clear lines of communication, coordination, and control, has become almost second nature. This largely unconscious embrace of the mechanistic approach to management has now become one of the main obstacles to organizational change.

3.7 Concluding remarks

As we move further into the twenty-first century, transcending the mechanistic view of organizations will be as critical for the survival of human civilization as transcending the mechanistic conceptions of health, the economy, or biotechnology. All these issues are linked, ultimately, to the profound scientific, social, and cultural transformation that is now under way with the emergence of the new systemic conception of life. In the following chapters, we shall discuss the rise of systems thinking in the twentieth century before turning to our detailed discussion of the biological, cognitive, social, and ecological dimensions of the systems view of life.

II

The rise of systems thinking

whole cannot be understood from the study of its parts alone. As the systems theorists would put it several decades later, the whole is more than the sum of its parts.

Vitalists and organismic biologists differed sharply in their answers to the question: In what sense exactly is the whole more than the sum of its parts? The vitalists asserted that some nonphysical entity, or force, must be added to the laws of physics and chemistry to understand life. Organismic biologists maintained that the additional ingredient is the understanding of "organization," or "organizing relations."

Since these organizing relations are patterns of relationships immanent in the physical structure of the organism, organismic biologists asserted that no separate, nonphysical entity is required for the understanding of life. Later on, the concept of organization was refined to that of "self-organization," which is still used in contemporary theories of living systems. Indeed, in these theories the understanding of the patterns of self-organization is the key to understanding the essential nature of life (as we discuss in Chapter 8).

4.1.2 Organismic biology

During the early twentieth century, organismic biologists, opposing both mechanism and vitalism, took up the problem of biological form with great enthusiasm. Some of the main characteristics of what we now call systems thinking emerged from their extensive reflections.

Ross Harrison (1870–1959), one of the early exponents of the organismic school, explored the concept of organization. He identified configuration and relationship as two important aspects of organization, which were subsequently unified in the concept of "pattern of organization" as a configuration of ordered relationships.

The biochemist Lawrence Henderson (1878–1942) was influential through his early use of the term "system" to denote both living organisms and social systems. From that time on, a system came to mean an integrated whole whose essential properties arise from the relationships between its parts, and "systems thinking" the understanding of a phenomenon within the context of a larger whole. This is, in fact, the root meaning of the word "system," which derives from the Greek *syn* + *histanai* ("to place together"). To understand things systemically means literally to put them into a context, to establish the nature of their relationships.

The biologist Joseph Woodger (1894–1981) asserted that organisms could be described completely in terms of their chemical elements, "plus organizing relations." This formulation had considerable influence on subsequent biological thought, and historians of science have stated that the publication of Woodger's *Biological Principles* in 1936 marked the end of the debate between mechanists and vitalists. Woodger and other organismic biologists also emphasized that one of the key characteristics of the organization of living organisms is its hierarchical nature.

Indeed, an outstanding property of all life is the tendency to form multileveled structures of systems within systems. Each of these forms a whole with respect to its parts while at the same time being a part of a larger whole. Thus, cells combine to form tissues, tissues to form organs, and organs to form organisms. These in turn exist within social systems and ecosystems. Throughout the living world, we find living systems nesting within other living systems.

The double role of living systems as parts and wholes requires the interplay of two opposite tendencies: an integrative tendency to function as part of a larger whole, and a self-assertive, or self-organizing tendency to preserve individual autonomy (see Chapter 7).

Since the early days of organismic biology, these multileveled structures of systems within systems have been called hierarchies. However, this term can be misleading, since it is derived from human hierarchies, which are fairly rigid structures of domination and control, quite unlike the multileveled order found in nature. We shall see in Section 4.1.5 that the important concept of living networks provides a new perspective on the so-called "hierarchies" of nature.

What the early systems thinkers recognized very clearly is the existence of different levels of complexity with different kinds of laws operating at each level. Thus the notion of "organized complexity" became another key concept. At each level of complexity, the observed phenomena exhibit properties that do not exist at the lower level. For example, the concept of temperature, which is central to thermodynamics, is meaningless at the level of individual atoms where the laws of quantum theory operate. In the early 1920s, the philosopher C.D. Broad (1887–1971) coined the term "emergent properties" for those properties that emerge at a certain level of complexity but do not exist at lower levels.

4.1.3 A new way of thinking

The ideas set forth by organismic biologists during the first half of the twentieth century helped to give birth to a new way of thinking – thinking in terms of connectedness, relationships, patterns, and context. According to the systems view, the essential properties of an organism, or living system, are properties of the whole, which none of the parts have. They arise from the interactions and relationships between the parts. These properties are destroyed when the system is dissected, either physically or theoretically, into isolated elements. Although we can discern individual parts in any system, these parts are not isolated, and the nature of the whole is always different from the mere sum of its parts. The systems view of life is illustrated beautifully and abundantly in the writings of Paul Weiss (1971, 1973), who brought systems concepts to the life sciences from his earlier studies of engineering and spent his whole life exploring and advocating a fully organismic conception of biology.

The emergence of systems thinking was a profound revolution in the history of Western scientific thought. The belief that in every complex system the behavior of the whole can be understood entirely from the properties of its parts is central to the Cartesian paradigm. This was Descartes' celebrated method of analytic thinking, which has been an essential characteristic of modern scientific thought. In the analytic, or reductionist, approach, the