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 askwhat 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.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Mechanism and holism in modern biology

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

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

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

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

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

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

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

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

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

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

When organismic biologists in Germany explored the concept of organic form, they engaged in dialogues with psychologists from the very beginning. The philosopher Christian von Ehrenfels (1859–1932) used the German word *Gestalt*, meaning "organic form," to describe an irreducible perceptual pattern, which sparked the school of Gestalt psychology. To characterize a Gestalt, Ehrenfels coined the celebrated phrase, "The whole is more than the sum of its parts," which would become the catchphrase of systems thinking later on.

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.

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