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From the Parts to the Whole

During this century the change from the mechanistic to the ecological paradigm has proceeded in different forms and at different speeds in the various scientific fields. It is not a steady change. It involves scientific revolutions, backlashes, and pendulum swings. A chaotic pendulum in the sense of chaos theory[1]—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." In this book I shall use "ecological" and "systemic" synonymously, "systemic" being merely the more technical, scientific term.

The main characteristics of systems thinking emerged simultaneously in several disciplines during the first half of the century, especially during the 1920s. Systems thinking was pioneered by biologists, who emphasized the view of living organisms as integrated wholes. It was further enriched by Gestalt psychology and the new science of ecology, and it had perhaps the most dramatic effects in quantum physics. Since the central idea of the new paradigm concerns the nature of life, let us first turn to biology.

Substance and Form

The tension between mechanism and holism has been a recurring theme throughout the history of biology. It is an inevitable consequence of the ancient dichotomy between substance (matter, structure, quantity) and form (pattern, order, quality). Biological form is more than shape, more than a static configuration of components in a whole. There is a continual flux of matter through a living organism, while its form is maintained. There is development, and there is evolution. Thus the understanding of biological form is inextricably linked to the understanding of metabolic and developmental processes.

At the dawn of Western philosophy and science, the Pythagoreans distinguished "number," or pattern, from substance, or matter, viewing it as something that limits matter and gives it shape. As Gregory Bateson put it:

> The argument took the shape of "Do you ask what it's made of—earth, fire, water, etc.?" Or do you ask, "What is its *pattern?*" Pythagoreans stood for inquiring into pattern rather than inquiring into substance.[2]

Aristotle, the first biologist in the Western tradition, also distinguished between matter and form but at the same time linked the two through a process of development.[3] In contrast with Plato, Aristotle believed that form had no separate existence but was immanent in matter. Nor could matter exist separately from form. Matter, according to Aristotle, contains the essential nature of all things, but only as potentiality. By means of form this essence becomes real, or actual. The process of the self-realization of the essence in the actual phenomena is by Aristotle called *entelechy* ("self-completion"). It is a process of development, a thrust toward full self-realization. Matter and form are the two sides of this process, separable only through abstraction.

Aristotle created a formal system of logic and a set of unifying concepts, which he applied to the main disciplines of his time—biology, physics, metaphysics, ethics, and politics. His philosophy and science dominated Western thought for two thousand years after his death, during which his authority became almost as unquestioned as that of the church.

Cartesian Mechanism

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. This radical change was brought about by the new discoveries in physics, astronomy, and mathematics known as the Scientific Revolution and associated with the names of Copernicus, Galileo, Descartes, Bacon, and Newton.[4]

Galileo Galilei banned quality from science, restricting it to the study of phenomena that could be measured and quantified. This has been a very successful strategy throughout modern science, but our obsession with quantification and measurement has also exacted a heavy toll. As the psychiatrist R. D. Laing put it emphatically:

> Galileo's program offers us a dead world: Out go sight, sound, taste, touch, and smell, and along with them have since gone esthetic and ethical sensibility, values, quality, soul, consciousness, spirit. Experience as such is cast out of the realm of scientific discourse. Hardly anything has changed our world more during the past four hundred years than Galileo's audacious program. We had to destroy the world in theory before we could destroy it in practice.[5]

René Descartes created the method of analytic thinking, which consists in breaking up complex phenomena into pieces to understand the behavior of the whole from the properties of its parts. 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 Descartes, 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, whose grand synthesis, Newtonian mechanics, was the crowning achievement of seventeenth-century science. In biology the greatest success of Descartes's mechanistic model was its application to the phenomenon of blood circulation by William Harvey. Inspired by Harvey's success, the physiologists of his time tried to apply the mechanistic method to describe other bodily functions, such as digestion and metabolism. These attempts were dismal failures, however, because the phenomena the physiologists tried to explain involved chemical processes that were unknown at the time and could not be described in mechanical terms. The situation changed significantly in the eighteenth century, when Antoine Lavoisier, the "father of modern chemistry," demonstrated that respiration is a special form of oxidation and thus confirmed the relevance of chemical processes to the functioning of living organisms.

In the light of the new science of chemistry, the simplistic mechanical models of living organisms were largely abandoned, but the essence of the Cartesian idea survived. Animals were still machines, although they were much more complicated than mechanical clockworks, involving 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. At the same time, the rigidly mechanistic physiology found its most forceful and elaborate expression in a polemic treatise *Man a Machine,* by Julien de La Mettrie, which remained famous well beyond the eighteenth century and generated many debates and controversies, some of which reached even into the twentieth century.[6]

The Romantic Movement

The first strong opposition to the mechanistic Cartesian paradigm came from the Romantic movement in art, literature, and philosophy in the late eighteenth and nineteenth centuries. William Blake, 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 these celebrated lines:

> May God us keep
> from single vision and Newton's sleep.[7]

The German Romantic poets and philosophers returned to the Aristotelian tradition by concentrating on the nature of organic form. Goethe, 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 admired nature's "moving order" *(bewegliche Ordnung)* and conceived of form as a pattern of relationships within an organized whole—a conception that is at the forefront of contemporary systems thinking. "Each creature," wrote Goethe, "is but a patterned gradation *(Schattierung)* of one great harmonious whole."[8] The Romantic artists were concerned mainly with a qualitative understanding of patterns, and therefore they placed great emphasis on explaining the basic properties of life in terms of visualized forms. Goethe, in particular, felt that visual perception was the door to understanding organic form.[9]

The understanding of organic form also played an important role in the philosophy of Immanuel Kant, who is often considered the greatest of the modern philosophers. An idealist, Kant separated the phenomenal world from a world of "things-in-themselves." He believed that science could offer only mechanical explanations, but he affirmed that in areas where such explanations were inadequate, scientific knowledge needed to be supplemented by considering nature as being purposeful. The most important of these areas, according to Kant, is the understanding of life.[10]

In his *Critique of Judgment* Kant discussed the nature of living organisms. He argued that organisms, in contrast with machines, are self-reproducing, self-organizing wholes. In a machine, according to Kant, the parts only exist *for* each other, in the sense of supporting each other within a functional whole. In an organism the parts also exist *by means of* each other, in the sense of producing one another.[11] "We must think of each part as an organ," wrote Kant, "that produces the other parts (so that each reciprocally produces the other). . . . Because of this, [the organism] will be both an organized and self-organizing being."[12] With this statement Kant became not only the first to use the term "self-organization" to define the nature of living organisms, he also used it in a way that is remarkably similar to some contemporary conceptions.[13]

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. The view of the Earth as being alive, of course, has a long tradition. Mythical images of the Earth Mother are among the oldest in human religious history. Gaia, the Earth Goddess, was revered as the supreme deity in early, pre-Hellenic Greece.[14] Earlier still, from the Neolithic through the Bronze Ages, the societies of "Old Europe" worshiped numerous female deities as incarnations of Mother Earth.[15]

The idea of the Earth as a living, spiritual being continued to flourish throughout the Middle Ages and the Renaissance, until the whole medieval outlook was replaced by the Cartesian image of the world as a machine. So when scientists in the eighteenth century began to visualize the Earth as a living being, they revived an ancient tradition that 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 hypothesis, and it is interesting that the views of the living Earth developed by eighteenth-century scientists contain some key elements of our contemporary theory.[16] The Scottish geologist James Hutton maintained that geological and biological processes are all interlinked

and compared the Earth's waters to the circulatory system of an animal. The German naturalist and explorer Alexander von Humboldt, one of the greatest unifying thinkers of the eighteenth and nineteenth centuries, took this idea even further. His "habit of viewing the Globe as a great whole" led Humboldt to identifying climate as a unifying global force and to recognizing the coevolution of living organisms, climate, and Earth crust, which almost encapsulates the contemporary Gaia hypothesis.[17]

At the end of the eighteenth and the beginning of the nineteenth centuries 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, who created a system of zoological classification based on similarities of structural relations.[18]

Nineteenth-Century Mechanism

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.[19] The nineteenth century is best known for the establishment 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 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 among the cellular building blocks.

Research in microbiology—a new field that revealed an unsuspected richness and complexity of microscopic living organisms—was dominated by the genius of Louis Pasteur, whose penetrating insights and clear formulations made a lasting impact in chemistry, biology, and medicine. Pasteur was able to establish the role of bacteria in certain chemical processes, thus laying the foundations of the new science of biochemistry, and he demonstrated that there is a definite correlation between "germs" (microorganisms) and disease.

Pasteur's discoveries 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 years earlier by Claude Bernard, the founder of modern experimental medicine. Bernard insisted on the close and intimate relation between an organism and its environment and was the first to point out that each organism also has an internal environment, in which its organs and tissues 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 Walter Cannon in the 1920s.

The new science of biochemistry progressed steadily and 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. This belief was most clearly expressed by Jacques Loeb in *The Mechanistic Conception of Life,* which had a tremendous influence on the biological thinking of its time.

Vitalism

The triumphs of nineteenth-century biology—cell theory, embryology, and microbiology—established the mechanistic conception of life as a firm dogma among biologists. Yet they carried within themselves the seeds of the next wave of opposition, the school known as organismic biology, or "organicism." While cell biology made enormous progress in understanding the structures and functions of many of the cell's subunits, it remained largely ignorant of the coordinating activities that integrate those operations into the functioning of the cell as a whole.

The limitations of the reductionist model were shown even more dramatically by the problems of cell development and differentiation. In the very early stages of the development of higher organisms, the number of their cells increases from one to two, to four, and so forth, doubling at each step. Since the genetic information is identical in each cell, how can these cells specialize in different ways, becoming muscle cells, blood cells, bone cells, nerve cells, and so on? This basic problem of development, which appears in many variations throughout biology, clearly flies in the face of the mechanistic view of life.

Before organicism was born, many outstanding biologists went through a phase of vitalism, and for many years the debate between mechanism and holism was framed as one between mechanism and vitalism.[20] A clear understanding of the vitalist idea is very useful, since it stands in sharp contrast with the systems view of life that was to emerge from organismic biology in the twentieth century.

Vitalism and organicism are both opposed to the reduction of biology to physics and chemistry. Both schools maintain that although the laws of physics and chemistry are applicable to organisms, they are insufficient to fully understand the phenomenon of life. The behavior of a living organism as an integrated 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 differ sharply in their answers to the question In what sense exactly is the whole more than the sum of its parts? Vitalists assert that some nonphysical entity, force, or field must be added to the laws of physics and chemistry to understand life. Organismic biologists maintain 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 assert that no separate, nonphysical entity is required for the understanding of life. We shall see later on that the concept of organization has been refined to that of "self-organization" in contemporary theories of living systems and that understanding the pattern of self-organization is the key to understanding the essential nature of life.

Whereas organismic biologists challenged the Cartesian machine analogy by trying to understand biological form in terms of a wider meaning of organization, vitalists did not really go beyond the Cartesian paradigm. Their language was limited by the same images and metaphors; they merely added a nonphysical entity as the designer or director of the organizing processes that defy mechanistic explanations. Thus the Cartesian split of mind and body led to both mechanism and vitalism. When Descartes's followers banned the mind from biology and conceived the body as a machine, the "ghost in the machine"—to use Arthur Koestler's phrase[21]—soon reappeared in vitalist theories.

The German embryologist Hans Driesch initiated the opposition to mechanistic biology at the turn of the century with his pioneering experiments on sea urchin eggs, which led him to formulate the first theory of vitalism. When Driesch destroyed one of the cells of an embryo at the very early two-celled stage, the remaining cell developed not into half a sea urchin, but into a complete but smaller organism. Similarly, complete smaller organisms developed after the destruction of two or three cells in four-celled embryos. Driesch realized that his sea urchin eggs had done what a machine could never do: they had regenerated wholes from some of their parts.

To explain this phenomenon of self-regulation, Driesch seems to have looked strenuously for the missing pattern of organization.[22] But instead of turning to the concept of pattern, he postulated a causal factor, for which he chose the Aristotelian term *entelechy*. However, whereas Aristotle's *entelechy* is a process of self-realization that unifies matter and form, the *entelechy* postulated by Driesch is a separate entity, acting on the physical system without being part of it.

The vitalist idea has been revived recently in much more sophisticated form by Rupert Sheldrake, who postulates the existence of nonphysical *morphogenetic* ("form-generating") fields as the causal agents of the development and maintenance of biological form.[23]

Organismic Biology

During the early twentieth century organismic biologists, opposing both mechanism and vitalism, took up the problem of biological form with new enthusiasm, elaborating and refining many of the key insights of Aristotle, Goethe, Kant, and Cuvier. Some of the main characteristics of what we now call systems thinking emerged from their extensive reflections.[24]

Ross Harrison, one of the early exponents of the organismic school, explored the concept of organization, which had gradually come to replace the old notion of function in physiology. This shift from function to organization represents a shift from mechanistic to systemic thinking, because function is essentially a mechanistic concept. Harrison identified configuration and relationship as two important aspects of organization, which were subsequently unified in the concept of pattern as a configuration of ordered relationships.

The biochemist Lawrence Henderson was influential through his early use of the term "system" to denote both living organisms and social systems.[25] From that time on, a system has come 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 *synhistanai* ("to place together"). To understand things systemically literally means to put them into a context, to establish the nature of their relationships.[26]

The biologist Joseph Woodger asserted that organisms could be described completely in terms of their chemical elements, "plus organizing relations." This formulation had considerable influence on Joseph Needham, who maintained that the publication of Woodger's *Biological Principles* in 1936 marked the end of the debate between mechanists and vitalists.[27] Needham, whose early work was on problems in the biochemistry of development, was always deeply interested in the philosophical and historical dimensions of science. He wrote many essays in defense of the mechanistic paradigm but subsequently came to embrace the organismic outlook. "A logical analysis of the concept of organism," he wrote in 1935, "leads us to look for organizing relations at all levels, higher and lower, coarse and fine, of the living structure."[28] Later on Needham left biology to become one of the leading historians of Chinese science and, as such, an ardent advocate of the organismic worldview that is the basis of Chinese thought.

Woodger and many others emphasized that one of the key characteristics of the organization of living organisms was 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.

Since the early days of organismic biology these multileveled structures have been called hierarchies. However, this term can be rather 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 that the important concept of the network—the web of life—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. Indeed, the concept of "organized complexity" became the very subject of the systems approach.[29] 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. Similarly, the taste of sugar is not present in the carbon, hydrogen, and oxygen atoms that constitute its components. In the early 1920s the philosopher C. D. Broad coined the

term "emergent properties" for those properties that emerge at a certain level of complexity but do not exist at lower levels.

Systems Thinking

The ideas set forth by organismic biologists during the first half of the century helped to give birth to a new way of thinking—"systems thinking"—in terms of connectedness, relationships, 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 among 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, who brought systems concepts to the life sciences from his earlier studies of engineering and spent his whole life exploring and advocating a full organismic conception of biology.[30]

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's celebrated method of analytic thinking, which has been an essential characteristic of modern scientific thought. In the analytic, or reductionist, approach, the parts themselves cannot be analyzed any further, except by reducing them to still smaller parts. Indeed, Western science has been progressing in that way, and at each step there has been a level of fundamental constituents that could not be analyzed any further.

The great shock of twentieth-century science has been that systems cannot be understood by analysis. The properties of the parts are not intrinsic properties but can be understood only within the context of the larger whole. Thus the relationship between the parts and the whole has been reversed. In the systems approach the properties of the parts can be understood only from the organization of the whole. Accordingly, systems thinking concentrates not on basic building blocks, but on basic principles of organization. Systems thinking is "contextual," which is the opposite of analytical thinking. Analysis means taking something apart in order to understand it; systems thinking means putting it into the context of a larger whole.

Quantum Physics

The realization that systems are integrated wholes that cannot be understood by analysis was even more shocking in physics than in biology. Ever since Newton, physicists had believed that all physical phenomena could be reduced to the properties of hard and solid material particles. In the 1920s, however, quantum theory forced them to accept the fact that the solid material objects of classical physics dissolve at the subatomic level into wavelike patterns of probabilities. These patterns, moreover, do not represent probabilities of things, but rather probabilities of interconnections. The subatomic particles have no meaning as isolated entities but can be understood only as interconnections, or correlations, among various processes of observation and measurement. In other words, subatomic particles are not "things" but interconnections among things, and these, in turn, are interconnections among other things, and so on. In quantum theory we never end up with any "things"; we always deal with interconnections.

This is how quantum physics shows that we cannot decompose the world into independently existing elementary units. As we shift our attention from macroscopic objects to atoms and subatomic particles, nature does not show us any isolated building blocks, but rather appears as a complex web of relationships among the various parts of a unified whole. As Werner Heisenberg, one of the founders of quantum theory, put it, "The world thus appears as a complicated tissue of events, in which connections of different kinds alternate or overlap or combine and thereby determine the texture of the whole."[31]

Molecules and atoms—the structures described by quantum physics—consist of components. However, these components, the

subatomic particles, cannot be understood as isolated entities but must be defined through their interrelations. In the words of Henry Stapp, "An elementary particle is not an independently existing unanalyzable entity. It is, in essence, a set of relationships that reach outward to other things."[32]

In the formalism of quantum theory these relationships are expressed in terms of probabilities, and the probabilities are determined by the dynamics of the whole system. Whereas in classical mechanics the properties and behavior of the parts determine those of the whole, the situation is reversed in quantum mechanics: it is the whole that determines the behavior of the parts.

During the 1920s the quantum physicists struggled with the same conceptual shift from the parts to the whole that gave rise to the school of organismic biology. In fact, the biologists would probably have found it much harder to overcome Cartesian mechanism had it not broken down in such a spectacular fashion in physics, which had been the great triumph of the Cartesian paradigm for three centuries. Heisenberg saw the shift from the parts to the whole as the central aspect of that conceptual revolution, and he was so impressed by it that he titled his scientific autobiography *Der Teil und das Ganze (The Part and the Whole).*[33]

Gestalt Psychology

When the first organismic biologists grappled with the problem of organic form and debated the relative merits of mechanism and vitalism, German psychologists contributed to that dialogue from the very beginning.[34] The German word for organic form is *Gestalt* (as distinct from *Form,* which denotes inanimate form), and the much discussed problem of organic form was known as the *Gestaltproblem* in those days. At the turn of the century, the philosopher Christian von Ehrenfels was the first to use *Gestalt* in the sense of an irreducible perceptual pattern, which sparked the school of Gestalt psychology. Ehrenfels characterized a gestalt by asserting that the whole is more than the sum of its parts, which would become the key formula of systems thinkers later on.[35]

Gestalt psychologists, led by Max Wertheimer and Wolfgang

Köhler, saw the existence of irreducible wholes as a key aspect of perception. Living organisms, they asserted, perceive things not in terms of isolated elements, but as integrated perceptual patterns—meaningful organized wholes, which exhibit qualities that are absent in their parts. The notion of pattern was always implicit in the writings of the Gestalt psychologists, who often used the analogy of a musical theme that can be played in different keys without losing its essential features.

Like the organismic biologists, Gestalt psychologists saw their school of thought as a third way beyond mechanism and vitalism. The Gestalt school made substantial contributions to psychology, especially in the study of learning and the nature of associations. Several decades later, during the 1960s, the holistic approach to psychology gave rise to a corresponding school of psychotherapy known as Gestalt therapy, which emphasizes the integration of personal experiences into meaningful wholes.[36]

In the Germany of the 1920s, the Weimar Republic, both organismic biology and Gestalt psychology were part of a larger intellectual trend that saw itself as a protest movement against the increasing fragmentation and alienation of human nature. The entire Weimar culture was characterized by an antimechanistic outlook, a "hunger for wholeness."[37] Organismic biology, Gestalt psychology, ecology, and, later on, general systems theory all grew out of this holistic zeitgeist.

Ecology

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

Ecology—from the Greek *oikos* ("household")—is the study of the Earth Household. More precisely it is the study of the relationships that interlink all members of the Earth Household. The

term was coined in 1866 by the German biologist Ernst Haeckel, who defined it as "the science of relations between the organism and the surrounding outer world."[38] In 1909 the word *Umwelt* ("environment") was used for the first time by the Baltic biologist and ecological pioneer Jakob von Uexküll.[39] In the 1920s ecologists focused on functional relationships within animal and plant communities.[40] In his pioneering book, *Animal Ecology,* Charles Elton introduced the concepts of food chains and food cycles, viewing the feeding relationships within biological communities as their central organizing principle.

Since the language of the early ecologists was very close to that of organismic biology, it is not surprising that they compared biological communities to organisms. For example, Frederic Clements, an American plant ecologist and pioneer in the study of succession, viewed plant communities as "superorganisms." This concept sparked a lively debate, which went on for more than a decade until the British plant ecologist A. G. Tansley rejected the notion of superorganisms and coined the term "ecosystem" to characterize animal and plant communities. The ecosystem concept—defined today as "a community of organisms and their physical environment interacting as an ecological unit"[41]—shaped all subsequent ecological thinking and, by its very name, fostered a systems approach to ecology.

The term "biosphere" was first used in the late nineteenth century by the Austrian geologist Eduard Suess to describe the layer of life surrounding the Earth. A few decades later the Russian geochemist Vladimir Vernadsky developed the concept into a full-fledged theory in his pioneering book, *Biosphere.*[42] Building on the ideas of Goethe, Humboldt, and Suess, Vernadsky saw life as a "geological force" that partly creates and partly controls the planetary environment. Among all the early theories of the living Earth, Vernadsky's comes closest to the contemporary Gaia theory developed by James Lovelock and Lynn Margulis in the 1970s.[43]

The new science of ecology enriched the emerging systemic way of thinking by introducing two new concepts—community and network. By viewing an ecological community as an assemblage of organisms, bound into a functional whole by their mutual relationships, ecologists facilitated the change of focus from organisms to communities and back, applying the same kinds of concepts to different systems levels.

Today we know that most organisms are not only members of ecological communities but are also complex ecosystems themselves, containing a host of smaller organisms that have considerable autonomy and yet are integrated harmoniously into the functioning of the whole. So there are three kinds of living systems—organisms, parts of organisms, and communities of organisms—all of which are integrated wholes whose essential properties arise from the interactions and interdependence of their parts.

Over billions of years of evolution many species have formed such tightly knit communities that the whole system resembles a large, multicreatured organism.[44] Bees and ants, for example, are unable to survive in isolation, but in great numbers they act almost like the cells of a complex organism with a collective intelligence and capabilities for adaptation far superior to those of its individual members. Similar close coordination of activities exists also among different species, where it is known as symbiosis, and again the resulting living systems have the characteristics of single organisms.[45]

From the beginning of ecology, ecological communities have been seen as consisting of organisms linked together in network fashion through feeding relations. This idea is found repeatedly in the writings of nineteenth-century naturalists, and when food chains and food cycles began to be studied in the 1920s, these concepts were soon expanded to the contemporary concept of food webs.

The "web of life" is, of course, an ancient idea, which has been used by poets, philosophers, and mystics throughout the ages to convey their sense of the interwovenness and interdependence of all phenomena. One of the most beautiful expressions is found in the celebrated speech attributed to Chief Seattle, which serves as the motto for this book.

As the network concept became more and more prominent in ecology, systemic thinkers began to use network models at all systems levels, viewing organisms as networks of cells, organs, and organ systems, just as ecosystems are understood as networks of individual organisms. Correspondingly, the flows of matter and energy through ecosystems were perceived as the continuation of the metabolic pathways through organisms.

The view of living systems as networks provides a novel perspective on the so-called hierarchies of nature.[46] Since living systems at all levels are networks, we must visualize the web of life as living systems (networks) interacting in network fashion with other systems (networks). For example, we can picture an ecosystem schematically as a network with a few nodes. Each node represents an organism, which means that each node, when magnified, appears itself as a network. Each node in the new network may represent an organ, which in turn will appear as a network when magnified, and so on.

In other words, the web of life consists of networks within networks. At each scale, under closer scrutiny, the nodes of the network reveal themselves as smaller networks. We tend to arrange these systems, all nesting within larger systems, in a hierarchical scheme by placing the larger systems above the smaller ones in pyramid fashion. But this is a human projection. In nature there is no "above" or "below," and there are no hierarchies. There are only networks nesting within other networks.

During the last few decades the network perspective has become more and more central to ecology. As the ecologist Bernard Patten put it in his concluding remarks to a recent conference on ecological networks: "Ecology *is* networks. . . . To understand ecosystems ultimately will be to understand networks."[47] Indeed, during the second half of the century the network concept has been the key to the recent advances in the scientific understanding not only of ecosystems but of the very nature of life.