THE WEB OF LIFE
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Preface

In 1944 the Austrian physicist Erwin Schrödinger wrote a short book entitled *What Is Life?* in which he advanced clear and compelling hypotheses about the molecular structure of genes. This book stimulated biologists to think about genetics in a novel way and in so doing opened a new frontier of science, molecular biology.

During subsequent decades, this new field generated a series of triumphant discoveries, culminating in the unraveling of the genetic code. However, these spectacular advances did not bring biologists any closer to answering the question posed in the title of Schrödinger's book. Nor were they able to answer the many associated questions that have puzzled scientists and philosophers for hundreds of years: How did complex structures evolve out of a random collection of molecules? What is the relationship between mind and brain? What is consciousness?

Molecular biologists have discovered the fundamental building blocks of life, but this has not helped them to understand the vital integrative actions of living organisms. Twenty-five years ago one of the leading molecular biologists, Sidney Brenner, made the following reflective comments:

> In one way, you could say all the genetic and molecular biological work of the last sixty years could be considered a long interlude. . . . Now that that program has been completed, we have come full circle—back to the problems left behind unsolved. How does a wounded organism regenerate to exactly the same structure it had before? How does the egg form the organism? . . . I think in the next twenty-five years we are going to have to teach biologists another language. . . . I don't know what it's called yet; nobody knows. . . . It may be wrong to believe that all the logic is at the molecular level. We may need to get beyond the clock mechanisms.[1]

Since the time Brenner made these comments, a new language for understanding the complex, highly integrative systems of life has indeed emerged. Different scientists call it by different names—"dynamical systems theory," "the theory of complexity," "nonlinear dynamics," "network dynamics," and so on. Chaotic attractors, fractals, dissipative structures, self-organization, and autopoietic networks are some of its key concepts.

This approach to understanding life is pursued by outstanding researchers and their teams around the world—Ilya Prigogine at the University of Brussels, Humberto Maturana at the University of Chile in Santiago, Francisco Varela at the Ecole Polytechnique in Paris, Lynn Margulis at the University of Massachusetts, Benoît Mandelbrot at Yale University, and Stuart Kauffman at the Santa Fe Institute, to name just a few. Several key discoveries of these scientists, published in technical papers and books, have been hailed as revolutionary.

However, to date nobody has proposed an overall synthesis that integrates the new discoveries into a single context and thus allows lay readers to understand them in a coherent way. This is the challenge and the promise of *The Web of Life.*

The new understanding of life may be seen as the scientific forefront of the change of paradigms from a mechanistic to an ecological worldview, which I discussed in my previous book *The Turning Point.* The present book, in a sense, is a continuation and expansion of the chapter in *The Turning Point* titled "The Systems View of Life."

The intellectual tradition of systems thinking, and the models and theories of living systems developed during the early decades of the century, form the conceptual and historical roots of the scientific framework discussed in this book. In fact, the synthesis of current theories and models I propose here may be seen as an outline of an emerging theory of living systems that offers a unified view of mind, matter, and life.

This book is for the general reader. I have kept the language as nontechnical as possible and have defined all technical terms where they first appear. However, the ideas, models, and theories I discuss are complex, and at times I felt the need to go into some technical detail to convey their substance. This applies particularly to some passages in chapters 5 and 6 and to the first part of chapter 9. Readers not interested in the technical details may want merely to browse through those passages and should feel free to skip them altogether without being afraid of losing the main thread of my argument.

The reader will also notice that the text includes not only numerous references to the literature, but also an abundance of cross-references to pages in this book. In my struggle to communicate a complex network of concepts and ideas within the linear constraints of written language, I felt that it would help to interconnect the text by a network of footnotes. My hope is that the reader will find that, like the web of life, the book itself is a whole that is more than the sum of its parts.

Berkeley, August 1995 FRITJOF CAPRA

1

Deep Ecology—A New Paradigm

This book is about a new scientific understanding of life at all levels of living systems—organisms, social systems, and ecosystems. It is based on a new perception of reality that has profound implications not only for science and philosophy, but also for business, politics, health care, education, and everyday life. It is therefore appropriate to begin with an outline of the broad social and cultural context of the new conception of life.

Crisis of Perception

As the century draws to a close, environmental concerns have become of paramount importance. We are faced with a whole series of global problems that are harming the biosphere and human life in alarming ways that may soon become irreversible. We have ample documentation about the extent and significance of these problems.[1]

The more we study the major problems of our time, the more we come to realize that they cannot be understood in isolation. They are systemic problems, which means that they are interconnected and interdependent. For example, stabilizing world population will be possible only when poverty is reduced worldwide.

The extinction of animal and plant species on a massive scale will continue as long as the Southern Hemisphere is burdened by massive debts. Scarcities of resources and environmental degradation combine with rapidly expanding populations to lead to the breakdown of local communities and to the ethnic and tribal violence that has become the main characteristic of the post–cold war era.

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 of us, 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. But this realization has not yet dawned on most of our political leaders. The recognition that a profound change of perception and thinking is needed if we are to survive has not yet reached most of our corporate leaders, either, or the administrators and professors of our large universities.

Not only do our leaders fail to see how different problems are interrelated; they also 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." The concept of sustainability has become a key concept in the ecology movement and is indeed crucial. Lester Brown of the Worldwatch Institute has given a simple, clear, and beautiful definition: "A sustainable society is one that satisfies its needs without diminishing the prospects of future generations."[2] This, in a nutshell, is the great challenge of our time: to create sustainable communities—that is to say, social and cultural environments in which we can satisfy our needs and aspirations without diminishing the chances of future generations.

The Paradigm Shift

My main interest in my life as a physicist has been in the dramatic change of concepts and ideas that occurred in physics during the first three decades of the century and is still being elaborated in our current theories of matter. The new concepts in physics have brought about a profound change in our worldview; from the mechanistic worldview of Descartes and Newton to a holistic, ecological view.

The new view of reality was by no means easy to accept for physicists at the beginning of the century. The exploration of the atomic and subatomic world brought them in contact with a strange and unexpected reality. In their struggle to grasp this new reality, scientists became painfully aware that their basic concepts, their language, and their whole way of thinking were inadequate to describe atomic phenomena. Their problems were not merely intellectual but amounted to an intense emotional and, one could say, even existential crisis. It took them a long time to overcome this crisis, but in the end they were rewarded with deep insights into the nature of matter and its relation to the human mind.[3]

The dramatic changes of thinking that happened in physics at the beginning of this century have been widely discussed by physicists and philosophers for more than fifty years. They led Thomas Kuhn to the notion of a scientific "paradigm," 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."[4] Changes of paradigms, according to Kuhn, occur in discontinuous, revolutionary breaks called "paradigm shifts."

Today, twenty-five years after Kuhn's analysis, we recognize the paradigm shift in physics as an integral part of a much larger cultural transformation. The intellectual crisis of the quantum physicists in the 1920s is mirrored today by a similar but much broader cultural crisis. Accordingly, what we are seeing is a shift of paradigms not only within science, but also in the larger social arena.[5] To analyze that cultural transformation I have generalized

Kuhn's definition of a scientific paradigm to that of a social paradigm, which I define 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."[6]

The paradigm that is now receding has dominated our culture for several hundred years, during which it has shaped our modern Western society and has significantly influenced the rest of the world. This paradigm consists of a number of entrenched ideas and values, among them the view of the universe as a mechanical system composed of elementary building blocks, the view of the human body as a machine, the view of life in society as a competitive struggle for existence, the belief in unlimited material progress to be achieved through economic and technological growth, and—last, but not least—the belief that a society in which the female is everywhere subsumed under the male is one that follows a basic law of nature. All of these assumptions have been fatefully challenged by recent events. And, indeed, a radical revision of them is now occurring.

Deep Ecology

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 two terms "holistic" and "ecological" differ slightly in their meanings, and it seems that "holistic" is somewhat less appropriate to describe the new paradigm. A holistic view of, say, a bicycle means to see the bicycle as a functional whole and to understand the interdependence of its parts accordingly. An ecological view of the bicycle includes that, but it adds to it the perception of how the bicycle is embedded in its natural and social environment—where the raw materials that went into it came from, how it was manufactured, how its use affects the natural environment and the community by which it is used, and so on. This distinction between "holistic" and "ecological" is even more important when we talk about living systems, for which the connections with the environment are much more vital.

The sense in which I use the term "ecological" is associated with a specific philosophical school and, moreover, with a global grass-roots movement known as "deep ecology," which is rapidly gaining prominence.[7] The philosophical school was founded by the Norwegian philosopher Arne Naess in the early 1970s with his distinction between "shallow" and "deep" ecology. This distinction is now 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, as the source of all value, and ascribes only instrumental, or "use," value to nature. Deep ecology does not separate humans—or anything else—from the natural environment. It sees the world not as a collection of isolated objects, but as a network of phenomena that are fundamentally interconnected and interdependent. Deep ecology recognizes the intrinsic value of all living beings and views humans as just one particular strand in the web of life.

Ultimately, deep ecological awareness is spiritual or religious awareness. When the concept of the human spirit is understood as the mode of consciousness in which the individual feels a sense of belonging, of connectedness, to the cosmos as a whole, it becomes clear that ecological awareness is spiritual in its deepest essence. It is, therefore, not surprising that the emerging new vision of reality based on deep ecological awareness is consistent with the so-called perennial philosophy of spiritual traditions, whether we talk about the spirituality of Christian mystics, that of Buddhists, or the philosophy and cosmology underlying the Native American traditions.[8]

There is another way in which Arne Naess has characterized deep ecology. "The essence of deep ecology," he says, "is to ask deeper questions."[9] This is also the essence of a paradigm shift.

We need to be prepared to question every single aspect of the old paradigm. Eventually we will not need to throw everything away, but before we know that we need to be willing to question everything. So deep ecology asks profound questions about the very foundations of our modern, scientific, industrial, growth-oriented, materialistic worldview and way of life. It questions this entire paradigm from an ecological perspective: from the perspective of our relationships to one another, to future generations, and to the web of life of which we are part.

Social Ecology and Ecofeminism

In addition to deep ecology, there are two other important philosophical schools of ecology, social ecology and feminist ecology, or "ecofeminism." In recent years there has been a lively debate in philosophical journals about the relative merits of deep ecology, social ecology, and ecofeminism.[10] It seems to me that each of the three schools addresses important aspects of the ecological paradigm and, rather than competing with each other, their proponents should try to integrate their approaches into a coherent ecological vision.

Deep ecological awareness seems to provide the ideal philosophical and spiritual basis for an ecological lifestyle and for environmental activism. However, it does not tell us much about the cultural characteristics and patterns of social organization that have brought about the current ecological crisis. This is the focus of social ecology.[11]

The common ground of the various schools of social ecology is the recognition that the fundamentally antiecological nature of many of our social and economic structures and their technologies is rooted in what Riane Eisler has called the "dominator system" of social organization.[12] Patriarchy, imperialism, capitalism, and racism are examples of social domination that are exploitative and antiecological. Among the different schools of social ecology there are various Marxist and anarchist groups who use their respective conceptual frameworks to analyze different patterns of social domination.

Ecofeminism could be viewed as a special school of social ecology, since it, too, addresses the basic dynamics of social domination within the context of patriarchy. However, its cultural analysis of the many facets of patriarchy and of the links between feminism and ecology go far beyond the framework of social ecology. Ecofeminists see the patriarchal domination of women by men as the prototype of all domination and exploitation in the various hierarchical, militaristic, capitalist, and industrialist forms. They point out that the exploitation of nature, in particular, has gone hand in hand with that of women, who have been identified with nature throughout the ages. This ancient association of woman and nature links women's history and the history of the environment and is the source of a natural kinship between feminism and ecology.[13] Accordingly, ecofeminists see female experiential knowledge as a major source for an ecological vision of reality.[14]

New Values

In this brief outline of the emerging ecological paradigm, I have so far emphasized the shifts in perceptions and ways of thinking. If that were all that were necessary, the transition to the new paradigm would be much easier. There are enough articulate and eloquent thinkers in the deep ecology movement who could convince our political and corporate leaders of the merits of the new thinking. But that is only part of the story. The shift of paradigms requires an expansion not only of our perceptions and ways of thinking, but also of our values.

Here it is interesting to note the striking connection in the changes between thinking and values. Both may be seen as shifts from self-assertion to integration. These two tendencies—the self-assertive and the integrative—are both essential aspects of all living systems.[15] Neither is intrinsically good or bad. What is good, or healthy, is a dynamic balance; what is bad, or unhealthy, is imbalance—overemphasis of one tendency and neglect of the other. If we now look at our Western industrial culture, we see that we have overemphasized the self-assertive and neglected the integrative tendencies. This is apparent both in our thinking and in our values, and it is very instructive to put these opposite tendencies side by side.

Thinking		*Values*	
Self-Assertive	*Integrative*	*Self-Assertive*	*Integrative*
rational	intuitive	expansion	conservation
analysis	synthesis	competition	cooperation
reductionist	holistic	quantity	quality
linear	nonlinear	domination	partnership

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

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

However, there is another kind of power, one that is more appropriate for the new paradigm—power as influence of others. The ideal structure for exerting this kind of power is not the hierarchy but the network, which, as we shall see, is also the central metaphor of ecology.[16] The paradigm shift thus includes a shift in social organization from hierarchies to networks.

Ethics

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

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

It is generally not recognized that values are not peripheral to science and technology but constitute their very basis and driving force. During the scientific revolution in the seventeenth century, values were separated from facts, and ever since that time we have tended to believe that scientific facts are independent of what we do and are therefore independent of our values. In reality, scientific facts emerge out of an entire constellation of human perceptions, values, and actions—in one word, out of a paradigm—from which they cannot be separated. Although much of the detailed research may not depend explicitly on the scientist's value system, the larger paradigm within which this research is pursued will never be value free. Scientists, therefore, are responsible for their research not only intellectually but also morally.

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

> Care flows naturally if the "self" is widened and deepened so that protection of free Nature is felt and conceived as protection of ourselves. . . . Just as we need no morals to make us breathe . . . [so] if your "self" in the wide sense embraces another being, you need no moral exhortation to show care. . . . You care for yourself without feeling any moral pressure to do it. . . . If reality is like it is experienced by the ecological self, our behavior *naturally* and beautifully follows norms of strict environmental ethics.[17]

What this implies is that the connection between an ecological perception of the world and corresponding behavior is not a logical but a *psychological* connection.[18] Logic does not lead us from the fact that we are an integral part of the web of life to certain norms of how we should live. However, if we have deep ecological awareness, or 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.

The link between ecology and psychology that is established by the concept of the ecological self has recently been explored by several authors. Deep ecologist Joanna Macy writes about "the greening of the self";[19] philosopher Warwick Fox has coined the term "transpersonal ecology";[20] and cultural historian Theodore Roszak uses the term "eco-psychology"[21] to express the deep connection between these two fields, which until very recently were completely separate.

Shift from Physics to the Life Sciences

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 point for science, because in the old paradigm physics has been the model and source of metaphors for all other sciences. "All philosophy is like a tree," wrote Descartes. "The roots are metaphysics, the trunk is physics, and the branches are all the other sciences."[22]

Deep ecology has overcome this Cartesian metaphor. Even though the paradigm shift in physics is still of special interest because it was the first to occur in modern science, physics has now lost its role as the science providing the most fundamental description of reality. However, 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. Today the paradigm shift in science, at its deepest level, implies a shift from physics to the life sciences.

2

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.

3

Systems Theories

By the 1930s most of the key criteria of systems thinking had been formulated by organismic biologists, Gestalt psychologists, and ecologists. In all these fields the exploration of living systems—organisms, parts of organisms, and communities of organisms—had led scientists to the same new way of thinking in terms of connectedness, relationships, and context. This new thinking was also supported by the revolutionary discoveries in quantum physics in the realm of atoms and subatomic particles.

Criteria of Systems Thinking

It is perhaps worthwhile to summarize the key characteristics of systems thinking at this point. The first, and most general, criterion is the shift from the parts to the whole. Living systems are integrated wholes whose properties cannot be reduced to those of smaller parts. Their essential, or "systemic," properties are properties of the whole, which none of the parts have. They arise from the "organizing relations" of the parts—that is, from a configuration of ordered relationships that is characteristic of that particular class of organisms, or systems. Systemic properties are destroyed when a system is dissected into isolated elements.

Another key criterion of systems thinking is the ability to shift one's attention back and forth between systems levels. Throughout the living world we find systems nesting within other systems, and by applying the same concepts to different systems levels—for example, the concept of stress to an organism, a city, or an economy—we can often gain important insights. On the other hand, we also have to recognize that, in general, different systems levels represent levels of differing complexity. At each level the observed phenomena exhibit properties that do not exist at lower levels. The systemic properties of a particular level are called "emergent" properties, since they emerge at that particular level.

In the shift from mechanistic thinking to systems thinking, the relationship between the parts and the whole has been reversed. Cartesian science believed that in any complex system the behavior of the whole could be analyzed in terms of the properties of its parts. Systems science shows that living 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 systems thinking is "contextual" thinking; and since explaining things in terms of their context means explaining them in terms of their environment, we can also say that all systems thinking is environmental thinking.

Ultimately—as quantum physics showed so dramatically—there are no parts at all. What we call a part is merely a pattern in an inseparable web of relationships. Therefore the shift from the parts to the whole can also be seen as a shift from objects to relationships. In a sense, this is a figure/ground shift. In the mechanistic view the world is a collection of objects. These, of course, interact with one another, and hence there are relationships among them. But the relationships are secondary, as illustrated schematically below in figure 3-1A. In the systems view we realize that the objects themselves are networks of relationships, embedded in larger networks. For the systems thinker the relationships are primary. The boundaries of the discernible patterns ("objects") are secondary, as pictured—again in greatly simplified fashion—in figure 3-1B.

The perception of the living world as a network of relationships

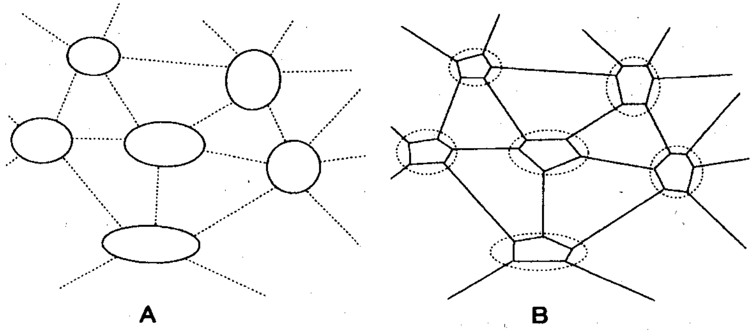

Figure 3-1
Figure/ground shift from objects to relationships.

has made thinking in terms of networks—expressed more elegantly in German as *vernetztes Denken*—another key characteristic of systems thinking. This "network thinking" has influenced not only our view of nature but also the way we speak about scientific knowledge. For thousands of years Western scientists and philosophers have used the metaphor of knowledge as a building, together with many other architectural metaphors derived from it.[1] We speak of *fundamental* laws, *fundamental* principles, *basic building blocks,* and the like, and we assert that the *edifice* of science must be built on firm *foundations.* Whenever major scientific revolutions occurred, it was felt that the foundations of science were moving. Thus Descartes wrote in his celebrated *Discourse on Method:*

> In so far as [the sciences] borrow their principles from philosophy, I considered that nothing solid could be built on such shifting foundations.[2]

Three hundred years later Heisenberg wrote in his *Physics and Philosophy* that the foundations of classical physics, that is, of the very edifice Descartes had built, were shifting:

> The violent reaction to the recent development of modern physics can only be understood when one realizes that here the foundations of physics have started moving; and that this motion has caused the feeling that the ground would be cut from under science.[3]

Einstein, in his autobiography, described his feelings in terms very similar to Heisenberg's:

> It was as if the ground had been pulled out from under one, with no firm foundation to be seen anywhere, upon which one could have built.[4]

In the new systems thinking, the metaphor of knowledge as a building is being replaced by that of the network. As we perceive reality as a network of relationships, our descriptions, too, form an interconnected network of concepts and models in which there are no foundations. For most scientists such a view of knowledge as a network with no firm foundations is extremely unsettling, and today it is by no means generally accepted. But as the network approach expands throughout the scientific community, the idea of knowledge as a network will undoubtedly find increasing acceptance.

The notion of scientific knowledge as a network of concepts and models, in which no part is any more fundamental than the others, was formalized in physics by Geoffrey Chew in his "bootstrap philosophy" in the 1970s.[5] The bootstrap philosophy not only abandons the idea of fundamental building blocks of matter, it accepts no fundamental entities whatsoever—no fundamental constants, laws, or equations. The material universe is seen as a dynamic web of interrelated events. None of the properties of any part of this web is fundamental; they all follow from the properties of the other parts, and the overall consistency of their interrelations determines the structure of the entire web.

When this approach is applied to science as a whole, it implies that physics can no longer be seen as the most fundamental level of science. Since there are no foundations in the network, the phenomena described by physics are not any more fundamental than those described by, say, biology or psychology. They belong to different systems levels, but none of those levels is any more fundamental than the others.

Another important implication of the view of reality as an inseparable network of relationships concerns the traditional concept of scientific objectivity. In the Cartesian paradigm scientific descriptions are believed to be objective—that is, independent of the human observer and the process of knowing. The new paradigm implies that epistemology—understanding of the process of knowing—has to be included explicitly in the description of natural phenomena.

This recognition entered into science with Werner Heisenberg and is closely related to the view of physical reality as a web of relationships. If we imagine the network pictured previously in figure 3-1B as much more intricate, perhaps somewhat similar to an inkblot in a Rorschach test, we can easily understand that isolating a pattern in this complex network by drawing a boundary around it and calling it an "object" will be somewhat arbitrary.

Indeed, this is what happens when we refer to objects in our environment. For example, when we see a network of relationships among leaves, twigs, branches, and a trunk, we call it a "tree." When we draw a picture of a tree, most of us will not draw the roots. Yet the roots of a tree are often as expansive as the parts we see. In a forest, moreover, the roots of all trees are interconnected and form a dense underground network in which there are no precise boundaries between individual trees.

In short, what we call a tree depends on our perceptions. It depends, as we say in science, on our methods of observation and measurement. In the words of Heisenberg: "What we observe is not nature itself, but nature exposed to our method of questioning."[6] Thus systems thinking involves a shift from objective to "epistemic" science, to a framework in which epistemology—"the method of questioning"—becomes an integral part of scientific theories.

The criteria of systems thinking described in this brief summary are all interdependent. Nature is seen as an interconnected web of relationships, in which the identification of specific patterns as "objects" depends on the human observer and the process of knowing. This web of relationships is described in terms of a corresponding network of concepts and models, none of which is any more fundamental than the others.

This new approach to science immediately raises an important question. If everything is connected to everything else, how can we ever hope to understand anything? Since all natural phenomena are ultimately interconnected, in order to explain any one of them we need to understand all the others, which is obviously impossible.

What makes it possible to turn the systems approach into a science is the discovery that there is approximate knowledge. This insight is crucial to all of modern science. The old paradigm is based on the Cartesian belief in the certainty of scientific knowledge. In the new paradigm it is recognized that all scientific concepts and theories are limited and approximate. Science can never provide any complete and definitive understanding.

This can be illustrated easily with a simple experiment that is often performed in introductory physics courses. The professor drops an object from a certain height and shows her students with a simple formula from Newtonian physics how to calculate the time it takes for the object to reach the ground. As with most of Newtonian physics, this calculation will neglect the resistance of the air and will therefore not be completely accurate. Indeed, if the object to be dropped were a feather, the experiment would not work at all.

The professor may be satisfied with this "first approximation," or she may want to go a step further and take the air resistance into account by adding a simple term to the formula. The result—the second approximation—will be more accurate but still not completely so, because air resistance depends on the temperature and pressure of the air. If the professor is very ambitious, she may derive a much more complicated formula as a third approximation, which would take these variables into account.

However, the air resistance depends not only on the temperature and air pressure, but also on the air convection—that is, on the large-scale circulation of air particles through the room. The students may observe that this air convection is caused, in addition to an open window, by their breathing patterns; and at this point the professor will probably stop the process of improving the approximation in successive steps.

This simple example shows that the fall of an object is connected in multiple ways to its environment—and, ultimately, to the rest of the universe. No matter how many connections we take into account in our scientific description of a phenomenon, we will always be forced to leave others out. Therefore scientists can never deal with truth, in the sense of a precise correspondence between the description and the described phenomenon. In science we always deal with limited and approximate descriptions of reality. This may sound frustrating, but for systems thinkers the fact that we *can* obtain approximate knowledge about an infinite web of interconnected patterns is a source of confidence and strength. Louis Pasteur said it beautifully:

> 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.[7]

Process Thinking

All the systems concepts discussed so far can be seen as different aspects of one great strand of systemic thinking, which we may call contextual thinking. There is another strand of equal importance, which emerged somewhat later in twentieth-century science. This second strand is process thinking. In the mechanistic framework of Cartesian science there are fundamental structures, and then there are forces and mechanisms through which these interact, thus giving rise to processes. In systems science every structure is seen as the manifestation of underlying processes. Systems thinking is always process thinking.

In the development of systems thinking during the first half of the century, the process aspect was first emphasized by the Austrian biologist Ludwig von Bertalanffy in the late 1930s and was further explored in cybernetics during the 1940s. Once the cyberneticists had made feedback loops and other dynamic patterns a central subject of scientific investigation, ecologists began to study the cyclical flows of matter and energy through ecosystems. For example, Eugene Odum's text *Fundamentals of Ecology,* which influenced a whole generation of ecologists, depicted ecosystems in terms of simple flow diagrams.[8]

Of course, like contextual thinking, process thinking, too, had its forerunners, even in Greek antiquity. Indeed, at the dawn of Western science we encounter Heraclitus' celebrated dictum: "Everything flows." During the 1920s the English mathematician and philosopher Alfred North Whitehead formulated a strongly process-oriented philosophy.[9] At the same time the physiologist Walter Cannon took up Claude Bernard's principle of the constancy of an organism's "internal environment" and refined it into the concept of homeostasis—the self-regulatory mechanism that allows organisms to maintain themselves in a state of dynamic balance with their variables fluctuating between tolerance limits.[10]

In the meantime, detailed experimental studies of cells had made it clear that the metabolism of a living cell combines order and activity in a way that cannot be described by mechanistic science. It involves thousands of chemical reactions, all taking place simultaneously to transform the cell's nutrients, synthesize its basic structures, and eliminate its waste products. Metabolism is a continual, complex, and highly organized activity.

Whitehead's process philosophy, Cannon's concept of homeostasis, and the experimental work on metabolism all had a strong influence on Ludwig von Bertalanffy, leading him to formulate a new theory of "open systems." Later on, during the 1940s, Bertalanffy enlarged his framework and attempted to combine the various concepts of systems thinking and organismic biology into a formal theory of living systems.

Tektology

Ludwig von Bertalanffy is commonly credited with the first formulation of a comprehensive theoretical framework describing the principles of organization of living systems. However, twenty to thirty years before he published the first papers on his "general systems theory," Alexander Bogdanov, a Russian medical researcher, philosopher, and economist, developed a systems theory of equal sophistication and scope, which unfortunately is still largely unknown outside of Russia.[11]

Bogdanov called his theory "tektology," from the Greek *tekton* ("builder"), which can be translated as "the science of structures." Bogdanov's main goal was to clarify and generalize the principles of organization of all living and nonliving structures:

> Tektology must clarify the modes of organization that are perceived to exist in nature and human activity; then it must generalize and systematize these modes; further it must explain them, that is, propose abstract schemes of their tendencies and laws. . . . Tektology deals with organizational experiences not of this or that specialized field, but of all these fields together. In other words, tektology embraces the subject matter of all the other sciences.[12]

Tektology was the first attempt in the history of science to arrive at a systematic formulation of the principles of organization operating in living and nonliving systems.[13] It anticipated the conceptual framework of Ludwig von Bertalanffy's general systems theory, and it also included several important ideas that were formulated four decades later, in a different language, as key principles of cybernetics by Norbert Wiener and Ross Ashby.[14]

Bogdanov's goal was to formulate a "universal science of organization." He defined organizational form as "the totality of connections among systemic elements," which is virtually identical to our contemporary definition of pattern of organization.[15] Using the terms "complex" and "system" interchangeably, Bogdanov distinguished three kinds of systems: organized complexes, where the whole is greater than the sum of its parts; disorganized complexes, where the whole is smaller than the sum of its parts; and neutral complexes, where the organizing and disorganizing activities cancel each other.

The stability and development of all systems can be understood, according to Bogdanov, in terms of two basic organizational mechanisms: formation and regulation. By studying both forms of organizational dynamics and illustrating them with numerous examples from natural and social systems, Bogdanov explores several key ideas pursued by organismic biologists *and* by cyberneticists.

The dynamics of formation consists in the joining of complexes through various kinds of linkages, which Bogdanov analyzes in great detail. He emphasizes in particular that the tension between crisis and transformation is central to the formation of complex systems. Foreshadowing the work of Ilya Prigogine,[16] Bogdanov shows how organizational crisis manifests itself as a breakdown of the existing systemic balance and at the same time represents an organizational transition to a new state of balance. By defining categories of crises, Bogdanov even anticipates the concept of catastrophe developed by the French mathematician René Thom, which is a key ingredient in the currently emerging new mathematics of complexity.[17]

Like Bertalanffy, Bogdanov recognized that living systems are open systems that operate far from equilibrium, and he carefully studied their regulation and self-regulation processes. A system for which there is no need of external regulation, because the system regulates itself, is called "bi-regulator" in Bogdanov's language. Using the example of the steam engine to illustrate self-regulation, as the cyberneticists would do several decades later, Bogdanov essentially described the mechanism defined as feedback by Norbert Wiener, which became a central concept of cybernetics.[18]

Bogdanov did not attempt to formulate his ideas mathematically, but he did envisage the future development of an abstract "tektological symbolism," a new kind of mathematics to analyze the patterns of organization he had discovered. Half a century later such a new mathematics has indeed emerged.[19]

Bogdanov's pioneering book, *Tektology,* was published in Russian in three volumes between 1912 and 1917. A German edition was published and widely reviewed in 1928. However, very little is known in the West about this first version of a general systems theory and precursor of cybernetics. Even in Ludwig von Bertalanffy's *General System Theory,* published in 1968, which includes a section on the history of systems theory, there is no reference to Bogdanov whatsoever. It is difficult to understand how Bertalanffy, who was widely read and published all his original work in German, would not have come across Bogdanov's work.[20]

Among his contemporaries Bogdanov was largely misunderstood because he was so far ahead of his time. In the words of the Azerbaijani scientist A. L. Takhtadzhian: "Foreign in its universality to the scientific thinking of the time, the idea of a general theory of organization was fully understood only by a handful of men and did not therefore spread."[21]

Marxist philosophers of the day were hostile to Bogdanov's ideas because they perceived tektology as a new philosophical system designed to replace that of Marx, even though Bogdanov protested repeatedly against the confusion of his universal science of organization with philosophy. Lenin mercilessly attacked Bogdanov as a philosopher, and consequently his works were suppressed for almost half a century in the Soviet Union. Recently, however, in the wake of Gorbachev's perestroika, Bogdanov's writings have received great attention from Russian scientists and philosophers. Thus it is to be hoped that Bogdanov's pioneering work will now be recognized more widely also outside Russia.

General Systems Theory

Before the 1940s the terms "system" and "systems thinking" had been used by several scientists, but it was Bertalanffy's concepts of an open system and a general systems theory that established systems thinking as a major scientific movement.[22] With the subsequent strong support from cybernetics, the concepts of systems thinking and systems theory became integral parts of the established scientific language and led to numerous new methodologies and applications—systems engineering, systems analysis, systems dynamics, and so on.[23]

Ludwig von Bertalanffy began his career as a biologist in Vienna during the 1920s. He soon joined a group of scientists and philosophers, known internationally as the Vienna Circle, and his work included broader philosophical themes from the very beginning.[24] Like other organismic biologists, he firmly believed that biological phenomena required new ways of thinking, transcending the traditional methods of the physical sciences. He set out to replace the mechanistic foundations of science with a holistic vision:

> General system theory is a general science of "wholeness" which up till now was considered a vague, hazy, and semi-metaphysical concept. In elaborate form it would be a mathematical discipline, in itself purely formal but applicable to the various empirical sciences. For sciences concerned with "organized wholes," it would be of similar significance to that which probability theory has for sciences concerned with "chance events."[25]

In spite of this vision of a future formal, mathematical theory, Bertalanffy sought to establish his general systems theory on a solid biological basis. He objected to the dominant position of physics within modern science and emphasized the crucial difference between physical and biological systems.

To make his point, Bertalanffy pinpointed a dilemma that had puzzled scientists since the nineteenth century, when the novel idea of evolution entered into scientific thinking. Whereas Newtonian mechanics was a science of forces and trajectories, evolutionary thinking—thinking in terms of change, growth, and development—required a new science of complexity.[26] The first formulation of this new science was classical thermodynamics with its celebrated "second law," the law of the dissipation of energy.[27] According to the second law of thermodynamics, formulated first by the French physicist Sadi Carnot in terms of the technology of thermal engines, there is a trend in physical phenomena from order to disorder. Any isolated, or "closed," 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."[28] According to the second law, the entropy of a closed physical system will keep increasing, and because this evolution is accompanied by increasing disorder, entropy can also be seen as a measure of disorder.

With the concept of entropy and the formulation of the second law, thermodynamics introduced the idea of irreversible processes, of an "arrow of time," into science. According to the second law, some mechanical energy is always dissipated into heat that cannot be completely recovered. Thus the entire world machine is running down and will eventually grind to a halt.

This grim picture of cosmic evolution was in sharp contrast with the evolutionary thinking among nineteenth-century biologists, who observed that the living universe evolves from disorder to order, toward states of ever-increasing complexity. At the end of the nineteenth century, then, Newtonian mechanics, the science of eternal, reversible trajectories, 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?

Ludwig von Bertalanffy could not resolve this dilemma, but he took the crucial first step by recognizing that living organisms are open systems that cannot be described by classical thermodynamics. He called such systems "open" because they need to feed on a continual flux of matter and energy from their environment to stay alive:

> The organism is not a static system closed to the outside and always containing the identical components; it is an open system in a (quasi-) steady state . . . in which material continually enters from, and leaves into, the outside environment.[29]

Unlike closed systems, which settle into a state of thermal equilibrium, open systems maintain themselves far from equilibrium in this "steady state" characterized by continual flow and change. Bertalanffy coined the German term *Fliessgleichgewicht* ("flowing balance") to describe such a state of dynamic balance. He recognized clearly that classical thermodynamics, which deals with closed systems at or near equilibrium, is inappropriate to describe open systems in steady states far from equilibrium.

In open systems, Bertalanffy speculated, entropy (or disorder) may decrease, and the second law of thermodynamics may not apply. He postulated that classical science would have to be complemented by a new thermodynamics of open systems. However, in the 1940s the mathematical techniques required for such an expansion of thermodynamics were not available to Bertalanffy. The formulation of the new thermodynamics of open systems had to wait until the 1970s. It was the great achievement of Ilya Prigogine, who used a new mathematics to reevaluate the second law by radically rethinking traditional scientific views of order and disorder, which enabled him to resolve unambiguously the two contradictory nineteenth-century views of evolution.[30]

Bertalanffy correctly identified the characteristics of the steady state as those of the process of metabolism, which led him to postulate self-regulation as another key property of open systems. This idea was refined by Prigogine thirty years later in terms of the self-organization of "dissipative structures."[31]

Ludwig von Bertalanffy's vision of a "general science of wholeness" was based on his observation that systemic concepts and principles can be applied in many different fields of study: "The parallelism of general conceptions or even special laws in different fields," he explained, "is a consequence of the fact that these are concerned with 'systems,' and that certain general principles apply to systems irrespective of their nature."[32] Since living systems span such a wide range of phenomena, involving individual organisms and their parts, social systems, and ecosystems, Bertalanffy believed that a general systems theory would offer an ideal conceptual framework for unifying various scientific disciplines that had become isolated and fragmented:

> General system theory should be . . . an important means of controlling and instigating the transfer of principles from one field to another, and it will no longer be necessary to duplicate or triplicate the discovery of the same principle in different fields isolated from each other. At the same time, by formulating exact criteria, general system theory will guard against superficial analogies which are useless in science.[33]

Bertalanffy did not see the realization of his vision, and a general science of wholeness of the kind he envisaged may never be formulated. However, during the two decades after his death in

1972, a systemic conception of life, mind, and consciousness began to emerge that transcends disciplinary boundaries and, indeed, holds the promise of unifying various fields of study that were formerly separated. Although this new conception of life has its roots more clearly in cybernetics than in general systems theory, it certainly owes a great deal to the concepts and thinking that Ludwig von Bertalanffy introduced into science.

4

The Logic of the Mind

While Ludwig von Bertalanffy worked on his general systems theory, attempts to develop self-guiding and self-regulating machines led to an entirely new field of investigation that had a major impact on the further development of the systems view of life. Drawing from several disciplines, the new science represented a unified approach to problems of communication and control, involving a whole complex of novel ideas, which inspired Norbert Wiener to invent a special name for it—"cybernetics." The word is derived from the Greek *kybernetes* ("steersman"), and Wiener defined cybernetics as the science of "control and communication in the animal and the machine."[1]

The Cyberneticists

Cybernetics soon became a powerful intellectual movement, which developed independently of organismic biology and general systems theory. The cyberneticists were neither biologists nor ecologists; they were mathematicians, neuroscientists, social scientists, and engineers. They were concerned with a different level of description, concentrating on patterns of communication, especially in closed loops and networks. Their investigations led them to the concepts of feedback and self-regulation and then, later on, to self-organization.

This attention to patterns of organization, which was implicit in organismic biology and Gestalt psychology, became the explicit focus of cybernetics. Wiener, especially, recognized that the new notions of message, control, and feedback referred to patterns of organization—that is, to nonmaterial entities—that are crucial to a full scientific description of life. Later on Wiener expanded the concept of pattern, from the patterns of communication and control that are common to animals and machines to the general idea of pattern as a key characteristic of life. "We are but whirlpools in a river of ever-flowing water," he wrote in 1950. "We are not stuff that abides, but patterns that perpetuate themselves."[2]

The cybernetics movement began during World War II, when a group of mathematicians, neuroscientists, and engineers—among them Norbert Wiener, John von Neumann, Claude Shannon, and Warren McCulloch—formed an informal network to pursue common scientific interests.[3] Their work was closely linked to military research that dealt with the problems of tracking and shooting down aircraft and was funded by the military, as was most subsequent research in cybernetics.

The first cyberneticists (as they would call themselves several years later) set themselves the challenge of discovering the neural mechanisms underlying mental phenomena and expressing them in explicit mathematical language. Thus while the organismic biologists were concerned with the material side of the Cartesian split, revolting against mechanism and exploring the nature of biological form, the cyberneticists turned to the mental side. Their intention from the beginning was to create an exact science of mind.[4] Although their approach was quite mechanistic, concentrating on patterns common to animals and machines, it involved many novel ideas that exerted a tremendous influence on subsequent systemic conceptions of mental phenomena. Indeed, the contemporary science of cognition, which offers a unified scientific conception of brain and mind, can be traced back directly to the pioneering years of cybernetics.

The conceptual framework of cybernetics was developed in a series of legendary meetings in New York City, known as the Macy Conferences.[5] These meetings—especially the first one in 1946—were extremely stimulating, bringing together a unique group of highly creative people who engaged in intense interdisciplinary dialogues to explore new ideas and ways of thinking. The participants fell into two core groups. The first formed around the original cyberneticists and consisted of mathematicians, engineers, and neuroscientists. The other group consisted of scientists from the humanities who clustered around Gregory Bateson and Margaret Mead. From the first meeting on, the cyberneticists made great efforts to bridge the academic gap between themselves and the humanities.

Norbert Wiener was the dominant figure throughout the conference series, imbuing it with his enthusiasm for science and dazzling his fellow participants with the brilliance of his ideas and often irreverent approaches. According to many witnesses Wiener had the disconcerting tendency to fall asleep during discussions, and even to snore, apparently without losing track of what was being said. Upon waking up, he would immediately make detailed and penetrating comments or point out logical inconsistencies. He thoroughly enjoyed these discussions and his central role in them.

Wiener was not only a brilliant mathematician, he was also an articulate philosopher. (In fact, his degree from Harvard was in philosophy.) He was keenly interested in biology and appreciated the richness of natural, living systems. He looked beyond the mechanisms of communication and control to larger patterns of organization and tried to relate his ideas to a wide range of social and cultural issues.

John von Neumann was the second center of attraction at the Macy Conferences. A mathematical genius, he had written a classic treatise on quantum theory, was the originator of the theory of games, and became world famous as the inventor of the digital computer. Von Neumann had a powerful memory, and his mind worked with enormous speed. It was said of him that he could understand the essence of a mathematical problem almost instantly and that he would analyze any problem, mathematical or practical, so clearly and exhaustively that no further discussion was necessary.

At the Macy meetings von Neumann was fascinated by the processes of the human brain and saw the description of brain functioning in formal logical terms as the ultimate challenge of science. He had tremendous confidence in the power of logic and great faith in technology, and throughout his work he looked for universal logical structures of scientific knowledge.

Von Neumann and Wiener had much in common.[6] Both were admired as mathematical geniuses, and their influence on society was far stronger than that of other mathematicians of their generation. They both trusted their subconscious minds. Like many poets and artists, they had the habit of sleeping with pencil and paper near their beds and made use of the imagery of their dreams in their work. However, these two pioneers of cybernetics differed significantly in their approach to science. Whereas von Neumann looked for control, for a program, Wiener appreciated the richness of natural patterns and sought a comprehensive conceptual synthesis.

In keeping with these characteristics, Wiener stayed away from people with political power, whereas von Neumann felt very comfortable in their company. At the Macy Conferences their different attitudes toward power, and especially toward military power, was the source of growing friction, which eventually led to a complete break. Whereas von Neumann remained a military consultant throughout his career, specializing in the application of computers to weapons systems, Wiener ended his military work shortly after the first Macy meeting. "I do not expect to publish any future work of mine," he wrote at the end of 1946, "which may do damage in the hands of irresponsible militarists."[7]

Norbert Wiener had a strong influence on Gregory Bateson, with whom he had a very good rapport throughout the Macy Conferences. Bateson's mind, like Wiener's, roamed freely across disciplines, challenging the basic assumptions and methods of several sciences by searching for general patterns and powerful universal abstractions. Bateson thought of himself primarily as a biologist and considered the many fields he became involved in—anthropology, epistemology, psychiatry, and others—as branches of biology. The great passion he brought to science embraced the full diversity of phenomena associated with life, and his main aim was to discover common principles of organization in that diversity—"the pattern which connects," as he would put it many years later.[8] At the cybernetics conferences Bateson and Wiener both searched for comprehensive, holistic descriptions while being careful to remain within the boundaries of science. In so doing, they created a systems approach to a broad range of phenomena.

His dialogues with Wiener and the other cyberneticists had a lasting impact on Bateson's subsequent work. He pioneered the application of systems thinking to family therapy, developed a cybernetic model of alcoholism, and authored the double-bind theory of schizophrenia, which had a major impact on the work of R. D. Laing and many other psychiatrists. However, Bateson's most important contribution to science and philosophy may have been the concept of mind, based on cybernetic principles, which he developed during the 1960s. This revolutionary work opened the door to understanding the nature of mind as a systems phenomenon and became the first successful attempt in science to overcome the Cartesian division between mind and body.[9]

The series of ten Macy Conferences was chaired by Warren McCulloch, professor of psychiatry and physiology at the University of Illinois, who had a solid reputation in brain research and made sure that the challenge of reaching a new understanding of mind and brain remained at the center of the dialogues.

The pioneering years of cybernetics resulted in an impressive series of concrete achievements, in addition to the lasting impact on systems thinking as a whole, and it is amazing that most of the novel ideas and theories were discussed, at least in their outlines, at the very first meeting.[10] The first conference began with an extensive description of digital computers (which had not yet been built) by John von Neumann, followed by von Neumann's persuasive presentation of analogies between the computer and the brain. The basis of these analogies, which were to dominate the cyberneticists' view of cognition for the subsequent three decades, was the use of mathematical logic to understand brain functioning, one of the outstanding achievements of cybernetics.

Von Neumann's presentations were followed by Norbert Wiener's detailed discussion of the central idea of his work, the concept of feedback. Wiener then introduced a cluster of new ideas, which coalesced over the years into information theory and communication theory. Gregory Bateson and Margaret Mead concluded the presentations with a review of the conceptual framework of the social sciences, which they considered inadequate and in need of basic theoretical work inspired by the new cybernetic concepts.

Feedback

All the major achievements of cybernetics originated in comparisons between organisms and machines—in other words, in mechanistic models of living systems. However, the cybernetic machines are very different from Descartes's clockworks. The crucial difference is embodied in Norbert Wiener's concept of feedback and is expressed in the very meaning of "cybernetics." A feedback loop is a circular arrangement of causally connected elements, in which an initial cause propagates around the links of the loop, so that each element has an effect on the next, until the last "feeds back" the effect into the first element of the cycle (see figure 4-1). The consequence of this arrangement is that the first link ("input") is affected by the last ("output"), which results in self-regulation of the entire system, as the initial effect is modified each time it travels around the cycle. Feedback, in Wiener's words, is the "control of a machine on the basis of its *actual* performance rather than its *expected* performance."[11] In a broader sense feedback has come to mean the conveying of information about the outcome of any process or activity to its source.

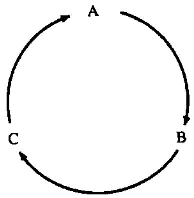

Figure 4-1
Circular causality of a feedback loop.

Wiener's original example of the steersman is one of the simplest examples of a feedback loop (see figure 4-2). When the boat deviates from the preset course—say, to the right—the steersman assesses the deviation and then countersteers by moving the rudder to the left. This decreases the boat's deviation, perhaps even to the point of moving through the correct position and then deviating to the left. At some time during this movement the steersman makes a new assessment of the boat's deviation, countersteers accordingly, assesses the deviation again, and so on. Thus he relies on continual feedback to keep the boat on course, its actual trajectory oscillating around the preset direction. The skill of steering a boat consists in keeping these oscillations as smooth as possible.

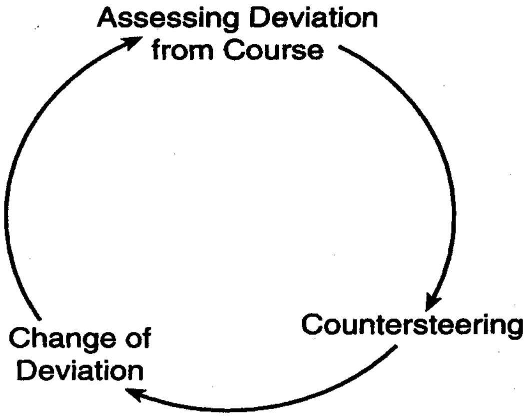

Figure 4-2
Feedback loop representing the steering of a boat.

A similar feedback mechanism is in play when we ride a bicycle. At first, when we learn to do so, we find it difficult to monitor the feedback from the continual changes of balance and to steer the bicycle accordingly. Thus a beginner's front wheel tends to oscillate strongly. But as our expertise increases, our brain monitors, evaluates, and responds to the feedback automatically, and the oscillations of the front wheel smooth out into a straight line.

Self-regulating machines involving feedback loops existed long before cybernetics. The centrifugal governor of a steam engine, invented by James Watt in the late eighteenth century, is a classic example, and the first thermostats were invented even earlier.[12] The engineers who designed these early feedback devices described their operations and pictured their mechanical components in design sketches, but they never recognized the pattern of circular causality embedded in them. In the nineteenth century the famous physicist James Clerk Maxwell wrote a formal mathematical analysis of the steam governor without ever mentioning the underlying loop concept. Another century had to go by before the connection between feedback and circular causality was recognized. At that time, during the pioneering phase of cybernetics, machines involving feedback loops became a central focus of engineering and have been known as "cybernetic machines" ever since.

The first detailed discussion of feedback loops appeared in a paper by Norbert Wiener, Julian Bigelow, and Arturo Rosenblueth, published in 1943 and titled "Behavior, Purpose, and Teleology."[13] In this pioneering article the authors not only introduced the idea of circular causality as the logical pattern underlying the engineering concept of feedback, but also applied it for the first time to model the behavior of living organisms. Taking a strictly behaviorist stance, they argued that the behavior of any machine or organism involving self-regulation through feedback could be called "purposeful," since it is behavior directed toward a goal. They illustrated their model of such goal-directed behavior with numerous examples—a cat catching a mouse, a dog following a trail, a person lifting a glass from a table, and so on—analyzing them in terms of the underlying circular feedback patterns.

Wiener and his colleagues also recognized feedback as the essential mechanism of homeostasis, the self-regulation that allows

living organisms to maintain themselves in a state of dynamic balance. When Walter Cannon introduced the concept of homeostasis a decade earlier in his influential book *The Wisdom of the Body,*[14] he gave detailed descriptions of many self-regulatory metabolic processes but never explicitly identified the closed causal loops embodied in them. Thus the concept of the feedback loop introduced by the cyberneticists led to new perceptions of the many self-regulatory processes characteristic of life. Today we understand that feedback loops are ubiquitous in the living world, because they are a special feature of the nonlinear network patterns that are characteristic of living systems.

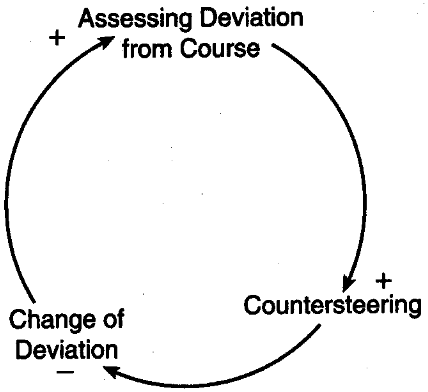

Figure 4-3
Positive and negative causal links.

The cyberneticists distinguished between two kinds of feedback—self-balancing (or "negative") and self-reinforcing (or "positive") feedback. Examples of the latter are the commonly known runaway effects, or vicious circles, in which the initial effect continues to be amplified as it travels repeatedly around the loop.

Since the technical meanings of "negative" and "positive" in this context can easily give rise to confusion, it may be worthwhile to explain them in more detail.[15] A causal influence from A to B is defined as positive if a change in A produces a change in B in the same direction—for example, an increase of B if A increases and a decrease if A decreases. The causal link is defined as negative if B changes in the opposite direction, decreasing if A increases and increasing if A decreases.

For example, in the feedback loop representing the steering of a boat, redrawn in figure 4-3, the link between "assessing deviation" and "countersteering" is positive—the greater the deviation from the preset course, the greater the amount of countersteering. The next link, however, is negative—the more the countersteering increases, the sharper the deviation will decrease. Finally, the last link is again positive. As the deviation decreases, its newly assessed value will be smaller than that previously assessed. The point to remember is that the labels "+" and "–" do not refer to an increase or decrease of value, but rather to the *relative direction of change* of the elements being linked—equal direction for "+" and opposite direction for "–".

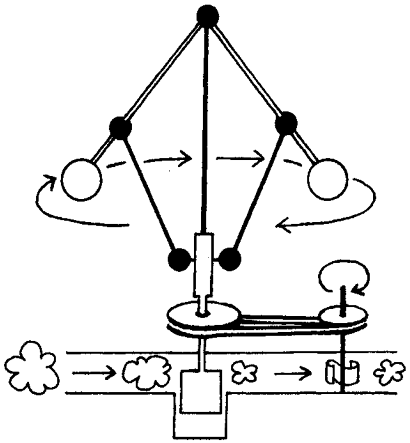

Figure 4-4
Centrifugal governor.

The reason why these labels are so convenient is that they lead to a very simple rule for determining the overall character of the feedback loop. It will be self-balancing ("negative") if it contains

an odd number of negative links and self-reinforcing ("positive") if it contains an even number of negative links.[16] In our example there is only one negative link; so the entire loop is negative, or self-balancing. Feedback loops are frequently composed of both positive and negative causal links, and their overall character is easily determined simply by counting the number of negative links around the loop.

The examples of steering a boat and riding a bicycle are ideally suited to illustrate the feedback concept, because they refer to well-known human experiences and are thus understood immediately. To illustrate the same principles with a mechanical device for self-regulation, Wiener and his colleagues often used one of the earliest and simplest examples of feedback engineering, the centrifugal governor of a steam engine (see figure 4-4). It consists of a rotating spindle with two weights ("flyballs") attached to it in such a way that they move apart, driven by the centrifugal force, when the speed of the rotation increases. The governor sits on top of the steam engine's cylinder, and the weights are connected with a piston, which cuts off the steam as they move apart. The pressure of the steam drives the engine, which drives a flywheel. The flywheel, in turn, drives the governor, and thus the loop of cause and effect is closed.

The feedback sequence is easily read off from the loop diagram drawn in figure 4-5. An increase in the speed of the engine increases the rotation of the governor. This increases the distance between the weights, which cuts down the steam supply. As the steam supply decreases, the speed of the engine decreases as well; the rotation of the governor slows down; the weights move closer together; steam supply increases; the engine speeds up again; and so on. The only negative link in the loop is the one between "distance between weights" and "steam supply," and therefore the entire feedback loop is negative, or self-balancing.

From the beginning of cybernetics, Norbert Wiener was aware that feedback is an important concept for modeling not only living organisms but also social systems. Thus he wrote in *Cybernetics:*

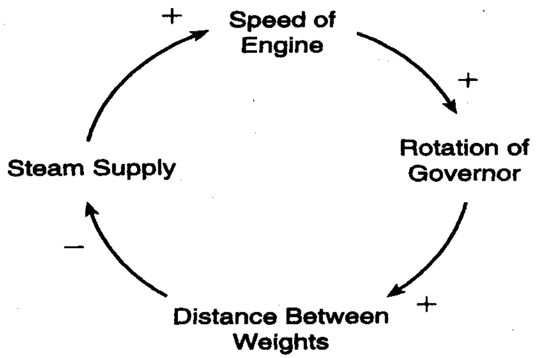

Figure 4-5
Feedback loop for centrifugal governor.

> It is certainly true that the social system is an organization like the individual, that is bound together by a system of communication, and that it has a dynamics in which circular processes of a feedback nature play an important role.[17]

It was the discovery of feedback as a general pattern of life, applicable to organisms and social systems, which got Gregory Bateson and Margaret Mead so excited about cybernetics. As social scientists they had observed many examples of circular causality implicit in social phenomena, and during the Macy meetings the dynamics of these phenomena were made explicit in a coherent unifying pattern.

Throughout the history of the social sciences numerous metaphors have been used to describe self-regulatory processes in social life. The best known, perhaps, are the "invisible hand" regulating the market in the economic theory of Adam Smith, the "checks and balances" of the U.S. Constitution, and the interplay of thesis and antithesis in the dialectic of Hegel and Marx. The phenomena described by these models and metaphors all imply circular patterns of causality that can be represented by feedback loops, but none of their authors made that fact explicit.[18]

If the circular logical pattern of self-balancing feedback was not recognized before cybernetics, that of self-reinforcing feedback had been known for hundreds of years in common parlance as a "vicious circle." The expressive metaphor describes a bad situation leading to its own worsening through a circular sequence of events. Perhaps the circular nature of such self-reinforcing, "runaway" feedback loops was recognized explicitly much earlier, because their effect is much more dramatic than the self-balancing of the negative feedback loops that are so widespread in the living world.

There are other common metaphors to describe self-reinforcing feedback phenomena.[19] The "self-fulfilling prophecy," in which originally unfounded fears lead to actions that make the fears come true, and the "bandwagon effect"—the tendency of a cause to gain support simply because of its growing number of adherents—are two well-known examples.

In spite of the extensive knowledge of self-reinforcing feedback in common folk wisdom, it played hardly any role during the first phase of cybernetics. The cyberneticists around Norbert Wiener acknowledged the existence of runaway feedback phenomena but did not study them any further. Instead they concentrated on the self-regulatory, homeostatic processes in living organisms. Indeed, purely self-reinforcing feedback phenomena are rare in nature, as they are usually balanced by negative feedback loops constraining their runaway tendencies.

In an ecosystem, for example, every species has the potential of undergoing an exponential population growth, but these tendencies are kept in check by various balancing interactions within the system. Exponential runaways will appear only when the ecosystem is severely disturbed. Then some plants will turn into "weeds," some animals become "pests," and other species will be exterminated, and thus the balance of the whole system will be threatened.

During the 1960s anthropologist and cyberneticist Magoroh Maruyama took up the study of self-reinforcing, or "deviation-amplifying" feedback processes in a widely read article, titled "The Second Cybernetics."[20] He introduced the feedback diagrams with "+" and "–" labels attached to their causal links, and he used this convenient notation for a detailed analysis of the interplay of negative and positive feedback processes in biological and social phenomena. In doing so, he linked the feedback concept of cybernetics with the notion of "mutual causality," which had been developed by social scientists in the meantime, and thus contributed significantly to the influence of cybernetic principles on social thought.[21]

From the point of view of the history of systems thinking, one of the most important aspects of the cyberneticists' extensive studies of feedback loops is the recognition that they depict patterns of organization. The circular causality in a feedback loop does not imply that the elements in the corresponding physical system are arranged in a circle. Feedback loops are abstract patterns of relationships embedded in physical structures or in the activities of living organisms. For the first time in the history of systems thinking, the cyberneticists clearly distinguished the pattern of organization of a system from its physical structure—a distinction that is crucial in the contemporary theory of living systems.[22]

Information Theory

An important part of cybernetics was the theory of information developed by Norbert Wiener and Claude Shannon in the late 1940s. It originated in Shannon's attempts at the Bell Telephone Laboratories to define and measure amounts of information transmitted through telegraph and telephone lines in order to estimate efficiencies and establish a basis for charging for messages.

The term "information" is used in information theory in a highly technical sense, which is quite different from our everyday use of the word and has nothing to do with meaning. This has resulted in endless confusion. According to Heinz von Foerster, a regular participant in the Macy Conferences and editor of the written proceedings, the whole problem is based on a very unfortunate linguistic error—the confusion between "information" and "signal," which led the cyberneticists to call their theory a theory of information rather than a theory of signals.[23]

Information theory, then, is concerned mainly with the problem of how to get a message, coded as a signal, through a noisy channel. However, Norbert Wiener also emphasized the fact that such a coded message is essentially a pattern of organization, and by drawing an analogy between such patterns of communication and the patterns of organization in organisms, he further prepared the ground for thinking about living systems in terms of patterns.

Cybernetics of the Brain

During the 1950s and 1960s Ross Ashby became the leading theorist of the cybernetics movement. Like McCulloch, Ashby was a neurologist by training, but he went much further than McCulloch in exploring the nervous system and constructing cybernetic models of neural processes. In his book *Design for a Brain,* Ashby attempted to explain in purely mechanistic and deterministic terms the brain's unique adaptive behavior, capacity for memory, and other patterns of brain functioning. "It will be assumed," he wrote, "that a machine or an animal behaved in a certain way at a certain moment because its physical and chemical nature at that moment allowed no other action."[24]

It is evident that Ashby was much more Cartesian in his approach to cybernetics than Norbert Wiener, who made a clear distinction between a mechanistic model and the nonmechanistic living system it represents. "When I compare the living organism with . . . a machine," wrote Wiener, "I do not for a moment mean that the specific physical, chemical, and spiritual processes of life as we ordinarily know it are the same as those of life-imitating machines."[25]

In spite of his strictly mechanistic outlook, Ross Ashby advanced the fledgling discipline of cognitive science considerably with his detailed analyses of sophisticated cybernetic models of neural processes. In particular he clearly recognized that living systems are energetically open while being—in today's terminology—organizationally closed: "Cybernetics might . . . be defined," wrote Ashby, "as the study of systems that are open to energy but closed to information and control—systems that are 'information-tight.' "[26]

Computer Model of Cognition

When the cyberneticists explored patterns of communication and control, the challenge to understand "the logic of the mind" and express it in mathematical language was always at the very center of their discussions. Thus for over a decade the key ideas of cybernetics were developed through a fascinating interplay among biology, mathematics, and engineering. Detailed studies of the human nervous system led to the model of the brain as a logical circuit with neurons as its basic elements. This view was crucial for the invention of digital computers, and that technological breakthrough in turn provided the conceptual basis for a new approach to the scientific study of mind. John von Neumann's invention of the computer and his analogy between computer and brain functioning are so closely intertwined that it is difficult to know which came first.

The computer model of mental activity became the prevalent view of cognitive science and dominated all brain research for the next thirty years. The basic idea was that human intelligence resembles that of a computer to such an extent that cognition—the process of knowing—can be defined as information processing—in other words, as manipulation of symbols based on a set of rules.[27]

The field of artificial intelligence developed as a direct consequence of this view, and soon the literature was full of outrageous claims about computer "intelligence." Thus Herbert Simon and Allen Newell wrote as early as 1958:

> There are now in the world machines that think, that learn and that create. Moreover, their ability to do these things is going to increase rapidly until—in the visible future—the range of problems they can handle will be coextensive with the range to which the human mind has been applied.[28]

This prediction is as absurd today as it was thirty-eight years ago, yet it is still widely believed. The enthusiasm among scientists and the general public for the computer as a metaphor for the human brain has an interesting parallel in the enthusiasm of Descartes and his contemporaries for the clock as a metaphor for the body.[29] For Descartes the clock was a unique machine. It was the only machine that functioned autonomously, running by itself once it was wound up. This was the time of the French Baroque, when clock mechanisms were widely used to build artful "lifelike" machinery, which delighted people with the magic of their seemingly spontaneous movements. Like most of his contemporaries, Descartes was fascinated by these automata, and he found it natural to compare their functioning to that of living organisms:

> We see clocks, artificial fountains, mills and other similar machines which, though merely man-made, have nonetheless the power to move by themselves in several different ways. . . . I do not recognize any difference between the machines made by craftsmen and the various bodies that nature alone composes.[30]

The clockworks of the seventeenth century were the first autonomous machines, and for three hundred years they were the only machines of their kind—until the invention of the computer. The computer is again a novel and unique machine. It not only moves autonomously once it is programmed and turned on, it does something completely new: it processes information. And since von Neumann and the early cyberneticists believed that the human brain, too, processes information, it was natural for them to use the computer as a metaphor for the brain and even for the mind, just as it had been for Descartes to use the clock as a metaphor for the body.

Like the Cartesian model of the body as a clockwork, that of the brain as a computer was very useful at first, providing an exciting framework for a new scientific understanding of cognition and leading to many fresh avenues of research. By the mid-1960s, however, the original model, which encouraged the exploration of its own limitations and the discussion of alternatives, had hardened into a dogma, as so often happens in science. During the subsequent decade almost all of neurobiology was dominated by the information-processing perspective, whose origins and underlying assumptions were hardly even questioned anymore.

Computer scientists contributed significantly to the firm establishment of the information-processing dogma by using expressions such as "intelligence," "memory," and "language" to describe computers, which led most people—including the scientists themselves—to think that these terms refer to the well-known human phenomena. This, however, is a grave misunderstanding, which has helped to perpetuate, and even reinforce, the Cartesian image of human beings as machines.

Recent developments in cognitive science have made it clear that human intelligence is utterly different from machine, or "artificial," intelligence. The human nervous system does not process any information (in the sense of discrete elements existing ready-made in the outside world, to be picked up by the cognitive system), but interacts with the environment by continually modulating its structure.[31] Moreover, neuroscientists have discovered strong evidence that human intelligence, human memory, and human decisions are never completely rational but are always colored by emotions, as we all know from experience.[32] Our thinking is always accompanied by bodily sensations and processes. Even if we often tend to suppress these, we always think *also* with our body; and since computers do not have such a body, truly human problems will always be foreign to their intelligence.

These considerations imply that certain tasks should never be left to computers, as Joseph Weizenbaum asserted emphatically in his classic book, *Computer Power and Human Reason.* These tasks include all those that require genuine human qualities such as wisdom, compassion, respect, understanding, or love. Decisions and communications that require those qualities will dehumanize our lives if they are made by computers. To quote Weizenbaum:

> A line dividing human and machine intelligence must be drawn. If there is no such line, then advocates of computerized psychotherapy may be merely the heralds of an age in which man has finally been recognized as nothing but clockwork. . . . The very asking of the question, "What does a judge (or psychiatrist) know that we cannot tell a computer?" is a monstrous obscenity.[33]

Impact on Society

Because of its link with mechanistic science and its strong connections to the military, cybernetics enjoyed a very high prestige among the scientific establishment right from the beginning. Over the years this prestige increased further as computers spread rapidly throughout all strata of industrial society, bringing about profound changes in every area of our lives. Norbert Wiener predicted those changes, which have often been compared to a second industrial revolution, during the early years of cybernetics. More than that, he clearly perceived the shadow side of the new technologies he had helped to create:

> Those of us who have contributed to the new science of cybernetics . . . stand in a moral position which is, to say the least, not very comfortable. We have contributed to the initiation of a new science which . . . embraces technical developments with great possibilities for good and for evil.[34]

> Let us remember that the automatic machine . . . is the precise economic equivalent of slave labor. Any labor which competes with slave labor must accept the economic conditions of slave labor. It is perfectly clear that this will produce an unemployment situation in comparison with which the present recession and even the depression of the thirties will seem a pleasant joke.[35]

It is evident from these and other similar passages in Wiener's writings that he showed much more wisdom and foresight in his assessment of the social impact of computers than his successors. Today, forty years later, computers and the many other "information technologies" developed in the meantime are rapidly becoming autonomous and totalitarian, redefining our basic concepts and eliminating alternative worldviews. As Neil Postman, Jerry Mander, and other technology critics have shown, this is typical of the "megatechnologies" that have come to dominate industrial societies around the world.[36] Increasingly, all forms of culture are being subordinated to technology, and technological innovation, rather than the increase in human well-being, has become synonymous with progress.

The spiritual impoverishment and loss of cultural diversity through excessive use of computers is especially serious in the field of education. As Neil Postman put it succinctly, "When a computer is used for learning, the meaning of 'learning' is changed."[37] The use of computers in education is often praised as a revolution that will transform virtually every facet of the educational process. This view is promoted vigorously by the powerful computer industry, which encourages teachers to use computers as educational tools at all levels—even in kindergarten and preschool!—without ever mentioning the many harmful effects that may result from these irresponsible practices.[38]

The use of computers in schools is based on the now outdated view of human beings as information processors, which continually reinforces erroneous mechanistic concepts of thinking, knowledge, and communication. Information is presented as the basis of thinking, whereas in reality the human mind thinks with ideas, not with information. As Theodore Roszak shows in detail in *The Cult of Information,* information does not create ideas; ideas create information. Ideas are integrating patterns that derive not from information but from experience.[39]

In the computer model of cognition, knowledge is seen as context and value free, based on abstract data. But all meaningful knowledge is contextual knowledge, and much of it is tacit and experiential. Similarly, language is seen as a conduit through which "objective" information is communicated. In reality, as C. A. Bowers has argued eloquently, language is metaphoric, conveying tacit understandings shared within a culture.[40] In this connection it is also important to note that the language used by computer scientists and engineers is full of metaphors derived from the military—"command," "escape," "fail-safe," "pilot," "target," and so on—which introduce cultural biases, reinforce stereotypes, and inhibit certain groups, including most young, school-age girls, from fully participating in the learning experience.[41] A related issue of concern is the connection between computers and the violence and militaristic nature of most computer-based video games.

After dominating brain research and cognitive science for thirty years and creating a paradigm for technology that is still widespread today, the information-processing dogma was finally questioned seriously.[42] Critical arguments had been presented already during the pioneering phase of cybernetics. For example, it was argued that in actual brains there are no rules; there is no central logical processor, and information is not stored locally. Brains seem to operate on the basis of massive connectivity, storing information distributively and manifesting a self-organizing capacity that is nowhere to be found in computers. However, these alternative ideas were eclipsed in favor of the dominant computational view, until they reemerged thirty years later during the 1970s, when systems thinkers became fascinated by a new phenomenon with an evocative name—self-organization.