6

ON THE SOCIAL NATURE OF AUTOPOIETIC SYSTEMS

Milan Zeleny

INTRODUCTION

Every organism, even if temporarily isolated, can emerge, survive, and reproduce only as part of a larger societal network of organisms. Similarly, each cell, organelle, or neuron can exist only as part of a group or society of cells, organelles, or neurons. Each component of an autopoietic (Varela *et al.*, 1974; Zeleny, 1980) system can emerge, persist, and reproduce only within the complex of relationships that constitute the network of interconnected components and component-producing processes.[1]

Before any organism can reproduce, it must first be produced (or self-produced), and it must survive. Autopoiesis therefore precedes, and in fact creates, the conditions for a subsequent reproduction.

Survival activities of individual organisms (economic and ecological) directly form and re-form local societies of interactive populations which are further concatenated into regional networks and full ecosystems. Reproductive organismic activities can take place only within such preformed networks and thus assure their own (networks') reinforcement and self-production. In fact, autopoietic systems can, and many do, adapt and evolve without their own reproduction; only their components may reproduce.

Eldredge (this volume) concludes that a gene-centered view of such systems is unnecessary, and that social networks are demonstrably biotic systems. The entire human society is such an autopoietic superorganism (Stock and Campbell, this volume) embedded in another autopoietic superorganism, Gaia—as is often propounded by L.Margulis (Mann, 1991).

The so-called "Gaia hypothesis" is, of course, not new in the history of science; A.A.Bogdanov formulated it quite early, clearly, autopoietically and with much elegance:

> The entire realm of life on earth can be considered as a single system of divergence, based on the rotation of carbon dioxide. This

> rotation forms a basis for complementary correlations between life as a whole—the "biosphere" —and the gaseous cover of the Earth—the "atmosphere." The stability of atmospheric content is sustained in the biosphere, which draws from the atmosphere the material for assimilation.
>
> (Zeleny, 1988a)

Bogdanov, the father of tectology (the precursor of modern autopoiesis), has thus conceptually coupled biosphere, atmosphere, hydrosphere, and lithosphere into a single holistic[2] system of mutually co-evolving influences.

Margulis has also targeted neo-Darwinism[3] and its inability to answer important questions or explain fundamental phenomena—for example, there is not a single case of a new species created by building up of chance mutations. She has embraced the so-called "autopoietic Gaia" (Mann, 1991).

Organisms cannot be separated (except through artificial cleavage) from their economic, ecological, or social environments which they themselves co-produce. Only a temporarily disembodied human mind can venture to remove itself, also temporarily, from its social surroundings—from its life base.

AUTOPOIESIS

> If Nature possesses a universal psyche, it is one far above the common and most impelling feelings of the human psyche. She certainly has never wept in sympathy, nor stretched a hand protectively over even the most beautiful or innocent of her creatures.
>
> (Eugène Marais, 1970)

Among the physical, biological, and social systems, the most complex and the most interesting ones are those which are autopoietic, i.e., autonomous and self-producing. The definition of these systems has been introduced by Varela, Maturana, and Uribe (1974). Also Haken (this volume), defining synergetics, refers to systems composed of many individual parts which, by their cooperation, can form organizations and structures—i.e., he refers to social systems.

An autopoietic system has been defined as a system that is generated through a closed organization of production processes such that the same organization of processes is regenerated through the interactions of its own products (components), and a boundary emerges as a result of the same constitutive processes.

Varela *et al.* (1974) have conceived autopoetic organization as an autonomous unity of a network of productions of components, which participate recursively in the same network of productions of components, which produced these components, and which realize such a network of productions as a unity in the space in which the components exist.

Such organization of components and component-producing processes remains essentially invariant through the interaction and turnover of components. The invariance follows from the definition: If the organization (the relations between system processes) changes substantially, there would be a change in the system's categorization in its identity class. What changes is the system's structure (its particular manifestation in the given environment) and its parts. The nature of the components and their spatiotemporal relations are secondary to their organization and thus refer only to the structure of the system.

System's boundary is a structural manifestation of the system's underlying organization. The boundary is a structural realization of the system in a particular environment of components. In physical environments this could take the form of a topological boundary. Both organization and structure are mutually interdependent.

The concepts of the autopoietic nature of a system were developed by Varela *et al.* (1974) based on a living (biological) system as a model of self-production. Yet self-production has the potential to mean and be interpreted in many different ways by a variety of observers. "Autopoiesis" has been coined (not translated from Greek) as a label for a clearly defined interpretation of "self-production." This phenomenon of self-production can be observed in living systems. A cell, a system that renews its macro-molecular components thousands of times during its lifetime, maintains its identity, cohesiveness, relative autonomy, and distinctiveness despite such turnover of matter. This persisting unity and its holism is called "autopoiesis."

Zeleny (1981) presents an overview of autopoiesis as a theory for the living organization. Varela *et al.* (1974) have developed a six-point key that provides the criteria for determining whether or not a system is autopoietically organized. These criteria, as they are applied to biological (living) systems, can also be applied to other systems that are currently not considered "living." This is a simple exercise with very important implications; yet it has not been carried out even by the "fathers" of autopoiesis. We have found (Zeleny and Hufford 1991, 1992) that not only are spontaneous social systems autopoietic, but also that the relationship is much stronger. Although all living systems are autopoietic, not all autopoietic systems are living. For example, inorganic osmotic growths (Zeleny *et al.,* 1989) are often autopoietic.

All autopoietic systems must be social systems. In other words, all autopoietic, and therefore all biological (living) systems, are social systems. Also, the topological boundary, that has been necessary to describe an autopoietic system within a favorable environment of physical components (such as those within and around a cell), may not necessarily take a physical form in other types of systems, e.g., in social systems.

In social systems, dynamic networks of productions are being continually renewed without changing their organization, while their components are being replaced; perishing or exiting individuals are substituted by the birth or entry of new members. Individual experiences are also renewed; ideas, concepts and their labels evolve and serve as the most important organizing factor in human societies. The organizing core for the implementation of ideas must be the emergent society as an autopoietic entity.

Autopoietic systems can persist in their autopoiesis for many decades (humans, trees), for many days (cells) or for mere flashes of hours, minutes, seconds, or milliseconds (osmotic growths). The time-measured "lifespan" of autopoiesis in no way enters (or should enter) into its definition. Also, autopoiesis is bound to exhibit gradation; it does not jump into being in a magic instant—it becomes. It gradually degrades itself; the processes of autopoiesis weaken and dim more or less rapidly (Zeleny, 1978).

There is a great modeling and explanatory potential, certainly on the rise in modern sciences, in treating autopoietic systems as social systems. At the same time, as a fringe benefit, it also disposes of the recently fashionable scholastic "discussions" as to whether social systems are or are not autopoietic.

SOCIAL SYSTEMS

> Have you ever seen, in some wood, on a sunny quiet day, a cloud of flying midges—thousands of them—hovering, apparently motionless, in a sunbeam? ... Yes? ... Well, did you ever see the whole flight—each mite apparently preserving its distance from all others—suddenly move, say three feet, to one side or the other? Well, what made them do that? A breeze? I said a quiet day. But try to recall—did you ever see them move directly back in the same unison? Well, what made them do that? Great human mass movements are slower of inception but much more effective.
>
> (Bernard M.Baruch, Foreword to Mackay (1849))

It is time to define social systems and to elucidate the meaning of "social" for the purposes of this chapter.

Social systems, in spite of all their rich metaphoric and anthropomorphic meanings and intuitions, are networks characterized by inner coordination of individual action achieved through communication among temporary agents. The key words are coordination, communication, and limited individual lifespan.[4]

Coordinated behavior includes both cooperation and competition, in all their shades and degrees. Actions of predation, altruism, and self-interest are simple examples of different and interdependent modes of coordination. Communication could be physically, chemically, visually, linguistically, or symbolically induced deformation (or in-formation) of the environment and consequently of individual action taking place in that environment.

So I, as an individual, can coordinate my own actions in the environment only if I coordinate it with the actions of other participants in the network. In order to achieve this, I have to in-form (change) the environment so that the actions of others are suitably modified; I have to communicate. As all other individuals are attempting to do the same a social network of coordination emerges, and, if successful, it is "selected" and persists. Such a network improves my ability to coordinate my own actions within the environment effectively. Cooperation, competition, altruism, and self-interest are therefore inseparable.

Social systems cannot be limited to human systems. Human systems simply in-form a special meaning on the universal acts of coordination, communication, and birth-death processes in general social systems.

A group of fish thrown together by a tide wave is a passive aggregation, not a social system. A swarm of moths lured to a porch light is an active aggregation, but not a social system. A flag-pattern of athletes constructed through bullhorn-shouted commands from a center is a purposeful heteropoietic aggregation, not a social system. All of these can transform into social systems as soon as internal communication patterns become established; they should then temporarily persist (become autonomous), even after removing the external impetus.

Mere externally induced interaction of components does not suffice; billiard balls interact and so do wind-blown grains of sand—nobody would call them social systems. Schools of fish, swarms of bees, flocks of birds, packs of animals, and even Barcelona wave-patterns of Olympic Games spectators are, however, no matter how ephemerally shortlived, exquisitely social systems.

Any social system, in order to adapt and persist in its environment, must be capable of reshaping itself, controlling its growth, and checking the proliferation of individuals. In other words, the long-term persistence of a social system is critically dependent on harmoniously balanced birth and death processes. There can be no life without death.

A proliferation of individuals without death processes and without death-inducing communication is "cancer" —a shortlived, environmentally destructive outburst of life-like processes, but not the life itself. A dominant death process, without a sufficient birth-process complement, takes any social system towards its extinction. Life of a social system, and thus life itself, is based on a dynamic and autopoietic harmony between birth and death processes. Life is necessarily a social phenomenon; the life of an individual cannot take place outside of a social network, and individual life itself must be socially embodied at the level of its components.

This view is quite different from the deterministic and essentially nonbiological dogma that (somehow) the growth of an organ is genetically (symbolically) programmed into the cells which are then guided (read-only memory) by this "geneprogram" through an exquisitely precise and predetermined series of events. But no communication and no death implies no life.

AUTOPOIESIS—THE SIX-POINT KEY

To determine whether a system is or is not autopoietic in its organization, Varela *et al.* (1974) have developed six key points or criteria that should be applied to a system. Their criteria can be stated as follows:

(1) Determine, through interactions, if the unity has identifiable boundaries. If the boundaries can be determined, proceed to (2). If not, the entity is indescribable and we can say nothing.
(2) Determine if there are constitutive elements of the unity, that is, components of the unity. If these components can be described, proceed to (3). If not, the unity is an unanalyzable whole and therefore not an autopoietic system.
(3) Determine if the unity is a mechanistic system, that is, the component properties are capable of satisfying certain relations that determine in the unity the interactions and transformations of these components. If this is the case proceed to (4). If not, the unity is not an autopoietic system.
(4) Determine if the components that constitute the boundaries of the unity constitute these boundaries through preferential neighborhood relations and interactions between themselves, as determined by their properties in the space of their interactions. If this is not the case, you do not have an autopoietic unity because you are determining its boundaries, not the unity itself. If (4) is the case, however, proceed to (5).
(5) Determine if the components of the boundaries of the unity are produced by the interactions of the components of the unity, either by transformation of previously produced components, or by transformations and/or coupling of non-component elements that enter the unity through its boundaries. If not, you do not have an autopoietic unity; if yes, proceed to (6).
(6) If all the other components of the unity are also produced by the interactions of its components as in (5), and if those which are not produced by the interactions of other components participate as necessary permanent constitutive components in the production of other components, you have an autopoietic unity in the space in which its components exist. If this is not the case and there are components in the unity not produced by components of the unity as in (5), or if there are components of the unity which do not participate in the production of other components, you do not have an autopoietic unity.

Thus, the successful application of the six-point key to a system will determine if the system is or is not autopoietically organized.

SYSTEMS ANALYSIS USING THE SIX-POINT KEY

To illustrate the diversity of autopoiesis in its application to systems analysis, Zeleny and Hufford (1991, 1992) have analyzed three systems: A biological (living) system, a chemical system, and a spontaneous social system. Here we summarize only the conclusions.

The eukaryotic cell

The generalized non-plant eukaryotic cell may be described as having a plasma membrane which surrounds the cytoplasm and cytoplasmic components of the cell. The cytoplasm contains the nucleus, mitochondria, golgi apparatus, endoplasmic reticulum, various vesicles, lysosomes, vacuoles, cytoplasmic filaments and microtubules, centrioles, and other components of the cell.

After applying the six-point key to the generalized eukaryotic cell, it can be concluded that the cell is an autopoietic unity in the space in which its components exist.

L.Margulis (Mann, 1991) is one of the few biologists who viewed eukaryotic cells as autopoietic populations of components. "We are walking communities," she insisted. Yet, this understanding of the role of symbiotic factors in biological organisms has been rarely carried beyond eukaryotes, to its logical conclusions.

Osmotic growth

Stephane Leduc (1911) described an " osmotic growth," a membrane of precipitated inorganic salt, as having many processes, functions, and characteristic forms that appear to be analogous to those found in living systems. The osmotic experiments performed by Leduc have been also reproduced by Klir, Hufford, and Zeleny (1988).

Unlike typical experiments in simple precipitation, where two solutions are mixed and a cloudy solution of an insoluble salt results, osmotic growths precipitate and grow over a period of minutes to days and go from a thin transparent membranous state to an opaque state. An actual photographic sequence has been provided by Zeleny, Klir, and Hufford (1989).

After applying the six-point test, based on the evaluation of osmotic growths (specifically the calcium chloride/tribasic sodium phosphate system), it can be concluded that an osmotic growth is an autopoietic unity in the space in which its components exist.

At the macroscopic level, the osmotic precipitation membrane exhibits fluidity, elasticity, and resealability identical to the properties of the plasma membrane. As the internal osmotic pressure increases, an expansion occurs (not a rupture) allowing components from the internal and external spaces to flow through the membrane and "couple" within the membrane. The osmotic growth phenomenon occurs because the operational integrity of the precipitation membrane is maintained.

At the microscopic level, the membrane exhibits various degrees of permeability to water and small ions in a fashion analogous to the plasma membrane. These features are a consequence of preferential neighborhood relations and interactions of the membrane components.

Osmotic growths are, temporarily and often ephemerally, autopoietic. This implies that if we hold the current autopoietic theory to be correct and intact, then we must reassess our definition (redefine our criteria) of what it means to be "living." If we do not give up our current definitions of "living," then we must conclude that there is a fundamental problem within the existing theory of autopoiesis which needs to be addressed.

Kinship system: a spontaneous social system

As our third system, the kinship system is an example of a spontaneous social order that has a substantial impact and great significance in the life of social, economic, and political networks. A kinship system constitutes, prototypically, an autopoietic system that is produced and maintained through organizational rules (which are potentially codified) of a given society. No matter what the particular mix of its components (men, women, and children), the kinship system organizes its social domain and coordinates its social action in a spontaneous self-perpetuating fashion. It must also continually adapt, spontaneously, to the external challenges and interferences of the society, represented by social engineers (shamans) and reformers.

Social networks, embodying kinship systems, are not static and unchanging structures, but highly dynamic ones.

Cochran *et al.* (1990), in their study of kinship systems, established that the distribution of different types and roles of network participants (kin, friends, neighbors, formal ties) remains relatively stable, even though the names and faces of network members keep changing. In the language of autopoiesis: It is their organization that remains stable, while their structures and components continually change.

Social networks can therefore change in their structure or in the nature of their component relationships (organization). One can therefore study shifts in the network's structure, turnover among its members, and changes in the character of continuing network ties. For example (Cochran *et al.,* 1990), in spite of frequent moving and changes of neighborhoods, American white children maintain the largest stable social networks (8 adults, 8 peers) while relatively immobile Swedish children maintained the smallest (4 adults, 4 peers).

Viewing families and kinship networks properly as autopoietic systems could lead to new and important understanding of the effects of residential mobility, divorce rates, death and disease disruptions, loss of employment, or state intervention on the structure, organization and durability of social bonds in important social and support networks—primary, functional, peripheral, and formal. Through social autopoiesis, one also can learn more about which social environments produce desirable social supports in transaction with parents. What is the role of friends and relatives? What is the role of parental self-confidence, and how can it be enhanced? What is the role of a parents' level of formal education? How do intervention programs interact with the spontaneous self-organizational nature of social autopoiesis? The research agenda of self-producing social systems is remarkable in its challenge and significance.

It was F.A.Hayek who integrated the concepts of self-production directly into the domain of social systems (1975). Hayek stated that:

> Although the overall order of actions arises in appropriate circumstances as the joint product of the actions of many individuals who are governed by certain rules, the production of the overall order is of course not the conscious aim of individual action since the individual will not have any knowledge of the overall order, so that it will not be an awareness of what is needed to preserve or restore the overall order in a particular moment but an abstract rule which will guide the actions of the individual.

Consequently, the individuals in a society spontaneously assume the sort of conduct which assures their existence within the whole. Of course this conduct must also be compatible with the preservation of the whole. Neither the society nor the individuals could exist if they did not behave in this manner. The overall order, preservation of the society, is not the "purpose" or the "plan" of the individuals. The individual actions are motivated by their own goals and purposes.

AMOEBA: BIOLOGICAL SOCIAL SYSTEMS

Howard Topoff (1981) asks:

> What do human beings, ants, and slime have in common? Despite their differences in structure, physiology and ecology, all three consist of individuals whose behavior is sufficiently coordinated for the group to be called a society.

The question is, is this "coordination" and the resulting society due to executing a preconceived plan of a social engineer, central planner, or a great designer (like in heteropoietic systems), or is it due to the distributed and unintended self-coordination of goal-seeking and autonomously behaving individuals (like in autopoietic systems)?

Cellular slime mold (Garfinkel, 1987) is another good example of an autopoietic social system. The slime molds (Gymnomycota) are an example of a fungus-like protist. They are decidedly fungus-like at some stages and animal-like at others. Their life cycle includes an ameoboid stage and a sedentary stage in which a fruiting-body develops and produces spores.

In Dictyostelium discoideum, a well-documented strain, the vegetative cell is amoeboid. Amoebas are individual cells moving around in search for bacteria to feed on. They will grow and divide indefinitely. Often they digest so much and produce new amoebas so rapidly that their food supply has no chance to replenish itself. When the food supply has been exhausted, they move rapidly to a central point, collecting themselves into a well-differentiated spontaneous aggregation (center cells, boundary cells, etc.) —a pseudoplasmodium. The aggregation is triggered by the production of cyclic adenosine monophosphate (AMP) which attracts other amoebas in a chemotactic fashion.

The group then assumes the shape of a "slug" with a head, tail, and an apparent "purpose": searching collectively for a new, potential source of food. Around the outside is secreted a mucoid sheath (aggregate boundary). It migrates as a unit across the substratum as a result of the collective action of the amoebas. The changing of the roles of individual amoebas is prevalent; the original leaders who formed the center of attraction are dispersed throughout the "slug", and new leaders emerge, forming the "goal-seeking" head.

The head of the home-hunting "slug" are simply the fastest-moving amoebas. The "slug" is just a spontaneous temporary metaorganism, preserving each amoeba as a separate individual. The slug is positively phototactic (migrates toward light), and it usually migrates for a period of hours. Its behavioral responses are essential "to ensure" that the spores will be borne in the air and so can be effectively dispersed.

Fruiting body formation begins when the slug ceases to migrate and becomes vertically oriented. The amoebas change quickly from the first to the last. The head of the slug forms the base of a stalk which follower-amoebas continue to build (they secrete cellulose to provide rigidity) up into a mushroom-like metaorganism. At its top, hundreds of thousands of amoebas differentiate into spores that are embedded in slime and, after the mushroom "head" matures, it bursts. It disperses the spores to new and potentially nourishing environments. When they fall to earth, they change once again into the individual amoebas which reproduce by cell division. This ecological cycle is then repeated.

AMOEBA: HUMAN SOCIAL SYSTEMS

> To the naive mind that can conceive of order only as the product of deliberate action, it may seem absurd that in complex conditions order, and adaptation to the unknown, can be achieved more effectively by decentralising decisions, and that

> division of authority will actually extend the possibility of overall order.
>
> (F.A.Hayek, 1988)

After the undisputed failures and fatal conceit of large-scale social engineering and experimentation of the past (Hayek, 1975, 1988), the phenomena of spontaneity and emergence in social systems are being emphasized again. Of significance are the surviving and robust social institutions such as market, family, culture, money, language, economy, city, and myriads of other voluntary orders. They have spontaneously emerged as a result of the natural (nonhuman engineered) formation and organization of society. The biological amoeba metaphor has recently found its organizational embodiment in the well-known "amoeba system" at Kyocera Corporation (Hamada and Monden, 1989). This system is also reminiscent of the famous Bata-system of management in the 1920s and 1930s in Moravia (Bata, 1992; Zeleny, 1988c).

The "amoebas" here are independent, profit-sharing and self-responsible units of three to fifty employees. Each amoeba carries out its own statistical control, profit system, cost accounting and personnel management. They compete, subcontract, and cooperate among themselves on the basis of the intracompany market of transfer prices.

Depending on the demand and amount of work, amoebas can divide into smaller units, move from one section of the factory to another, or integrate with other amoebas or departments. All amoebas are continually on the lookout for a better buyer for their intermediate products. Many amoebas even produce the same or similar products. They are authorized, as in the Bata-system (Zeleny, 1988c), to trade intermediate products with outside companies; if the internal vendor is unreasonable, the buyer amoeba will search for a satisfactory supplier outside the company.

A most remarkable feature towards autonomy is the member trading. Heads of amoebas lend and borrow members and so eliminate losses caused by surplus labor. So, Kyocera's amoebas multiply, disband, and form new units in the spirit of autopoiesis (self-production) of the enterprise. Amoeba division and breakup are everyday occurrences and are based on the criteria of output and a worker's added value per hour. This concept of ultimate flexibility is best summed up by Kyocera's President Inamori: "Development is the continued repetition of construction and destruction" (Hamada and Monden, 1989), as if coming directly from the systems theories of autopoietic self-organization.

Neither age nor training are essential to become the head of an amoeba—only the faculty for the job under the immediate circumstances. If unsuitable, amoeba heads are replaced immediately.

This system represents quite a revolutionary step beyond the traditional Toyota "just-in-time" system. At Kyocera, orders received by the sales department are passed directly to the amoeba of the final process. The rest of the amoebas in the preceding processes are then given free rein in entering into mutual contracts: the intracompany market takes over. Kyocera Corporation is one of the most profitable companies in Japan.

BOUNDARIES OF SOCIAL SYSTEMS

In kinship systems, boundaries are usually well defined. The distinction between family and non-family members is rarely ambiguous or subject to fuzzy interpretation. A definite family boundary can be established, although it is not necessarily topological. In the context of the family, the concept of boundary might be defined as the members included in a set. Family members are usually distinguished from their environment (from the "society") more sharply than any engineered or designed physical "membrane" can assure. Based on the six-point evaluation, the family is an autopoietic unity defined in the space of its own components.

All social systems, and thus all living systems, create, maintain, and degrade their own boundaries. These boundaries do not separate but intimately connect the system with its environment. They do not have to be just physical or topological, but are primarily functional, behavioral, and communicational. They are not "perimeters" but functional constitutive components of a given system.[6]

Boundaries do not exist for the observer to see or identify, but for the system and its components to communicate with its environment. These boundaries range from phospholipid bilayers, globular proteins, osmotic precipitates, and electric potentials, through cell layers, tissues, skins, metabolic barriers, and peripheral neural synapses, to laterally or upwardly dispersed boundaries of territorial markers, lines of scrimmage, social castes, secret initiation rites, and possessions of information, power, or money.

A company can have a number of geographically separate offices or be entirely "in the air" of electronic communication. The USA includes Alaska and Hawaii. A doctor does not leave the social system of a hospital while "on call" or connected with a beeper. Many additional examples and details of non-topological social boundaries are discussed by Miller and Miller (1992).

Although social systems are necessarily physical because their components realize their dynamic network of productions in the physical domain (their components are cells, termites, lions, adult humans, etc.), many computer simulations (Zeleny, 1978) of autopoietic systems show that topological boundaries arise only if very minute rates of production processes are very finely adjusted and harmonized. In other words, the underlying organization of processes has to be "tuned into." If not, a human observer might not be able to "see" or recognize any "topological" boundary. Yet the organization remains functional and invariant; autopoiesis continues; we do not see any boundary, but the system remains autopoietic.

Thus, topological boundary cannot occupy any definitional or "divine" position; it is the entire system (the entire biological cell) that reveals the underlying autopoiesis of production processes, not just some of its components (e.g., the boundary, cell membrane).

It is often easier to climb or even destroy a Berlin Wall, or to escape from Sing-Sing, than to become a member of an elite club or cross the subtle boundaries of race, habit, and culture.

The fact that a human observer or scientist cannot identify, see or touch a topological boundary of a given system cannot prove anything about the system's autopoiesis—except perhaps the observer's lack of adequate tools, correct models, or requisite intelligence.

ALL AUTOPOIETIC SYSTEMS ARE SOCIAL SYSTEMS

Recent advances in the areas of artificial life (Langton, 1989), synthetic biology, and osmotic growths (Klir *et al.,* 1988; Leduc, 1911; Zeleny *et al.,* 1989) have established that at least some autopoietic systems are nonbiological, i.e., self-producing in inorganic milieus.

Autopoiesis can take place only where there are separate and autonomously individual components interacting and communicating in a specific environment according to specific behavioral (including birth and death) rules of interaction. This is why autopoiesis (autopoietic organization) can be studied by postulating each component as a separate entity and tracing its behavior through cellular automata types of computer simulation.

Approaches which sacrifice this essential individuality of components, like the statistical systems of differential equations used in the traditional systems sciences, cannot model autopoiesis. This is because they are definitionally incapable of treating autopoietic systems as social systems. Components and participants in autopoiesis must follow rules, interact, and communicate—they must form a community of components, a society, a social system.

That the sciences of physics, chemistry, and biology are capable of treating their object systems as statistical masses, and not as social systems of communicating components, is bad enough. But that even the social systems proper (i.e., human systems) are also treated as differential mathematical equations, thus destroying their "social" quality, is inexplicable. Even though all autopoietic systems are social systems, social systems themselves are not often treated as autopoietic systems.

As F.A.Hayek (1988) pointed out, social engineers assume that since people have been able to generate some systems of rules coordinating their efforts, they must also be able to design an even better and "improved" system. The traditional norms or reason guiding the imposition and subsequent restructuring of socialism embody a naive and uncritical theory of rationality, an obsolete and unscientific methodology which Hayek calls "constructivist rationalism" and which E.L.Khalil (1990) traced to Karl Marx's concept of social labor.

Although the family (and other spontaneous social orders (Zeleny, 1985, 1991b)) can easily produce and generate systems other than itself, its primary capability is that of producing (and reproducing) itself. Concentration camps and other "engineered" societies are capable of heteropoiesis (producing "else") but are not capable of autopoiesis (producing "self"), except through sustained external force or coercion. The removal of such external pressures and props is one of the safest tests of viability (i.e., autopoiesis) of social systems. If the coercive boundaries (physical or otherwise) dissolve, and the social system ceases to exist, it was not autopoietic; if it reasserts its social boundary and voluntarily increases the level of cohesiveness, then it is autopoietic and self-sustaining.

It is only in the sense of such centrally-imposed "command" systems that we present our hypothesis: All autopoietic (biological) systems are social systems, but they are not hierarchical systems of command. Social organization can be defined as a network of interactions, reactions, and processes involving, at least:

(1) Production (poiesis): the rules and regulations guiding the entry of new living components (such as emergence, birth, membership, acceptance).
(2) Bonding (linkage): the rules of guiding associations, functions, and positions of individuals during their tenure within the organization.
(3) Degradation (disintegration): the rules and processes associated with the termination of membership (death, separation, expulsion).

In Figure 6.1 we graphically represent the above three poietic processes and connect them into a cycle of self-production. Observe that all such circularly concatenated processes represent productions of components necessary for other processes, not only the one designated as "production." To emphasize this crucial point we speak of poiesis instead of production and autopoiesis instead of self-production. Although in reality hundreds of processes could be so interconnected, the above three-process model represents the minimum conditions necessary for autopoiesis to emerge.

From the vantage point of Figure 6.1, all biological (autopoietic) systems are social systems. They consist of production, linkage, and disintegration of related components and component-producing processes. An organism or a cell is, therefore, a social system. Without the understanding of the poiesis of their components, we cannot even hope to understand them as wholes.

Australian TCG (Technical Computer Graphics) provides a good example of a self-producing network in a business-firm environment. There are no coordinating divisions, "leading firms," or management superstructures guiding TCG's twenty-four companies; the coherence, growth and maintenance of the network is produced, according to J.Mathews (1992), by a set of network-producing rules:

(1) Mutual independence through bilateral commercial contracts.
(2) Mutual preference in the letting of contracts.
(3) Mutual non-competition among members.
(4) Mutual non-exploitation among members.
(5) Flexibility and business autonomy; no group approval needed.

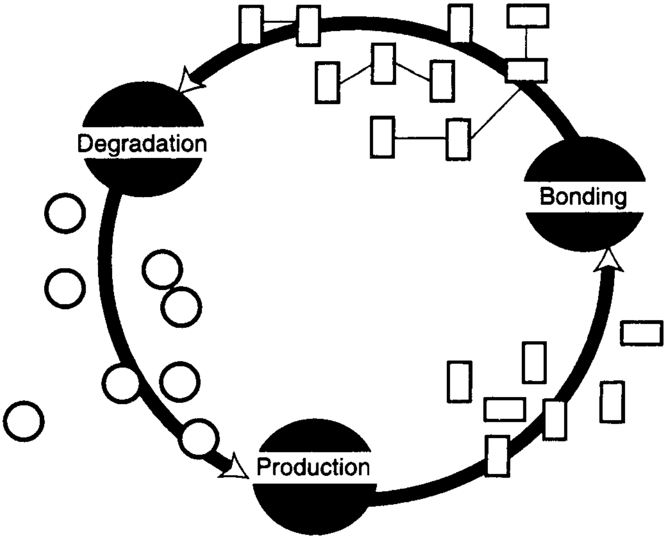

Figure 6.1 Circular organization of interdependent processes and their "productions"

(6) Network democracy without "central committee" or formal governance structure.
(7) Non-observance of rules leads to expulsion.
(8) All members equal access to the external open market.
(9) Entry: new members welcome, but not through drawing on group resources.
(10) Exit: no impediments to departing firms.

TCG network grows through a "triangulation process" (TCG plus external company plus a customer) and through spinning-off new companies.

Marvin Minsky has titled his book *The Society of Mind* (1986), attempting to exploit the social metaphor in studying the mind as a society. According to Minsky, mind is neither a unified, homogeneous "black box" or entity, nor a collection of entities, but a heterogeneous system of networks of processes. Unfortunately, Minsky's view of "society" is the hierarchy of agents (or experts), based on extreme division of labor (Zeleny, 1988b), each of them doing "some simple things that needs no mind or thought at all." Minsky writes like a social engineer of command systems, with little awareness of spontaneous social orders (Zeleny, 1985):

"…when *we* [italics M.Z.] join these agents in societies—in a certain and special way—this leads to true intelligence." The society has truly a very special meaning to Minsky (Minsky, 1986).

Minsky has made a very small step by calling mind, but not all biological systems, a society. He also revealed that by society he understands artificial hierarchies and heterarchies of specialized computeroid-agents. No self-organization and self-management of such agents emerges (Minsky, 1986). But a step has been taken; there is a benefit to be derived from studying complex biological systems as social systems.

G.M.Edelman improves upon Minsky by stating, as if responding directly and more eloquently than we ever could, to our query:

> Any satisfactory developmental theory of higher brain function must remove the need for homunculi and electricians at any level and at the same time must account for object definition and generalization from a world whose events and "objects" are not prelabeled by any a priori scheme or top-down order.
>
> (Edelman, 1988)

BIOLOGICAL ORGANISMS AS SOCIAL SYSTEMS

> The body of a mammal with its many vital organs can be looked upon as a community with specialized individuals grouped into organs, the whole community forming the composite animal.
>
> (Eugène Marais, 1970)

Although here we cannot analyze living systems in specialist's detail, let us explore the cellular organism, including the human organism, as a social system. Living organisms have often been studied as "black boxes," or as component-free machines, by mechanistic cybernetics. Therefore, no social-system view of life or the living could have emerged; no study of *inner* communication and birth-death processes was encouraged. Only a signal-feedback exploration of external responses of a uniform and homogeneous black box was proposed, with the obvious results.

Biological organisms are not component-free black boxes but communicating and birth-death process balancing social systems. Jim Michaelson of Harvard is one of the few biologists who is prepared to treat biological systems as social systems, positing the "competition" of cells, the selection and survival of the most "fit" during their embryonic development, as being dependent on the cell's ability to secrete enzymes, rate of proliferation, etc.

Communication

Whenever a living cell is unable to communicate with other cells, it does not die, but rather grows uncontrollably, multiplying into other non-communicating cells, forming a malignant tumor which is unable to survive in its life-sustaining environment because it destroys it.

All organismic cells are interconnected through tiny channels in cell membranes or gap junctions. Through these channels, all molecular, chemical, metabolic, and electric communication among cells takes place. These communicative junctions are made of proteins (connexins) that align all cells into one, continuous channel-network: a social system.

Malfunction in intercellular communication channels affects the intercellular social system and thus could "kill" the organism itself. If regulatory and inhibitory signals do not get through, the uncontrolled, deathless growth, and the voracious feeding on its own environment, would result.

Cancer, a variety of malignant tumors, can kill the entire social system of an organism via uncontrolled growth of small subsystems. Both lack of communication *per se* or good communication of wrong messages could lead to the breakdown in the social system of an organism. A good and clear communication system tends to suppress the spontaneous formation of tumors, but it could also help to proliferate wrong signals of malfunctioning components. The Catch-22: one abnormal cell could spell organismic doom if it is not held incommunicado, but if a normal cell becomes isolated, it could go abnormal quickly.

To study cancer processes without studying cellular gap junctions amounts to a case of professional neglect. Clogged channels block social-regulatory signals and allow cells to go awry; clear channels allow the propagation of deadly signals. Gap junctions themselves are selective self-regulatory; they tend to close and protect against chaotic signals and to open for and receive regulatory signals.

Even a fetus could not develop if particular groups of cells would not stop reproducing and growing "just-in-time," or more precisely, would not start dying. There would be no organ, no hand—just a cancerous, suicidal cellmass.

In order to treat cancers, one has either to re-establish communication channels and thus self-regulation or block communication channels in order to stop rampant proliferation, depending on the cancer source type. This is not a trivial mechanistic task, but it can only be mastered if we start viewing biological systems as social systems.

Social neighborhoods

As discussed in an American Association for the Advancement of Science (AAAS) symposium volume (Zeleny, 1980), cellular neighborhoods, rather than some inheritable genetic "programs," are the main determinants of cells' functions. Autopoietic systems are illustrated better by the American plan of development, where one's status and fate are determined by one's neighborhood, and not by the British plan, where one's status and fate are determined by one's ancestors.[7]

The neural network especially, i.e., the autonomous autopoietic system embedded in a larger complex of organismic networks, requires quick-response flexibility and adaptability which cannot wait for a mutations buildup or rely on requisite but cumbersome "genetic alterations." Neural networks develop as autopoietic societies; individual cells wander around, get exposed to differential signalings of different cellular neighborhoods, and ultimately settle down (or get captured) within these neighborhoods, becoming functioning neurons of the visual, hearing, or smell regions of the cerebral cortex. "Look, Ma, no genes!"

As H.Maturana insists in the above volume, "genes" and viral DNA are structural components of autopoiesis. Their distribution and mutation therefore affect structures and structural characteristics (inheritable shapes and adhesion properties of proteins), but they do not partake in organization; they do not organize matter, but are themselves organized and ordered by autopoiesis. If the neurons of the cortex are not prefixed and do not carry a "complete code" of how to behave, then they cannot provide the organizing principle of the brain and thus certainly not of the organism as a whole.

The greatest mistake biologists could make at this paradigmatic bifurcation point is searching for the seat of the master plan behind the body's gray matter. There is no master plan; spontaneous social systems (i.e., also biological systems) do not rely on their "Gorbachevs," and that is why they can persist. There are no black-box feedback loops within feedback loops; there is only a society in autopoiesis, organizing matter of different structural attributes and properties (including viral DNA), thus arriving at different, sometimes important, structural manifestations. Dr C.L. Cepko of Harvard Medical School puts it quite bluntly: "The mother cells do not impart specific information to their daughters about what to become."

Death process

In addition to communication, social systems are also characterized by limited lifespans of individual components, i.e., by death. If molecules would not break down, or cells, organisms, individuals and entire species would not die, there would be no social systems and thus no self-sustaining life on earth.

Death dominates development. The vestigial webbing between human fetus fingers must be dissolved before birth. About 80 per cent of the nerve cells of the baby's brain must perish within hours of their creation. No biologist can claim to be studying life without studying death. Caterpillar's crawling muscles must be sloughed off in order to have a butterfly; female genitalia must be whittled away in order to have a male.

Yet uncontrolled and massive death is non-redeeming; Alzheimer's, Parkinson's, and Lou Gehrig's degenerative disorders result. Uncontrolled and massive birth is equally unredeeming; cancerous cellmasses, killing their own environment (i.e., organism) result. Individuals must die in order to maintain their social system. So the species must die in order to maintain *theirs*—the Gaia. Why biologists study protein production and cell proliferation, while at the same time neglecting protein degradation and cell death amounts to one of the great mysteries of life. Is it the result of extreme specialization (Zeleny, 1988b), where some study only the "ins" and others only the "outs" of intellectual intercourse? Can such be a way towards understanding "conception"?

Death is not a chaotic, haphazard, or disorganized part of social system autopoiesis; it is a harmonized, choreographed, and often suicidal dance of the most exquisite complexity. The creation of autopoiesis is inconceivable without the trimming of apoptosis, and the study of apoptosis is crucial in biology: in fact, no true biology can exist without it.[8] Death is not the absence of life, but the crucial building block of life. Life is never "individual" life, but life of a social network of balanced and communicating birth-death processes. Death is not a passive default but an active system-creative response to intrasystemic, unity-maintaining signaling. A good example is the immune system. Millions of T and B cells are continually generated, each capable of assaulting foreign proteins, but unfortunately also the body's own proteins. Up to 98 per cent of them have to undergo immediate apoptosis in order to maintain the body's autopoiesis in a hostile environment.

Death is a productive process of the social system; it creates space, it generates production substrate, it brings in the innovation, and it allows trial-and-error adaptation to the environment. Individual cells are created in order to die, and thus their social system, i.e., living organism, can persist. The same principle is repeated at other levels, all the way to the Gaia and the Universe.

Evolution

> The idea that reason, itself created in the course of evolution, should now be in a position to determine its own future evolution is inherently contradictory, and can readily be refuted.
> (F.A.Hayek, 1988)

Social systems persist. They can persist as societies of agents only if their individual agents are born, communicate, and die in harmony with themselves and their environment. Because of the turnover of components, the social networks not only persist and are renewed, but they also evolve.

The unit of evolution (at any level) must be a network capable of a variety of self-organizing configurations. The entire social networks, including neuronal groups (Edelman, 1992) are being "selected," not their individual components. These evolving networks are interwoven and co-evolving with their environment; they do not only adapt to the environment, but also adapt the environment to themselves—through intimate structural coupling. Margolis (Mann, 1991) also insists that not the individual, but the symbiotic system, characterized primarily by autopoiesis, is the proper unit of biological study and symbiosis the major force behind evolution.

A bird must undoubtedly adapt to a mountain. A society (network) of birds can make the mountain adapt to them. By overconsuming particular berries, the new brush growth is controlled, the mountain's erosion enhanced, and the production of both berries and birds thus limited until a temporary balance or harmony is restored. Colors of flowers have co-evolved with the trichromatic vision of bees; shapes of flowers with the structural traits of insects and animals; modern breeders with the changing tastes and preferences of man. To quote R.Lewontin:

> The environment is not a structure imposed on living beings from the outside but is in fact a creation of those beings. The environment is not an autonomous process, but a reflection of the biology of the species. Just as there is no organism without an environment, so there is no environment without an organism.
>
> (Lewontin, 1983)

Varela *et al.* (1991), in their book *The Embodied Mind,*[9] conform to the view that living beings and their environments stand in relation to each other through mutual specification or codetermination: "The world is not a landing pad into which organisms parachute; nature and nurture stand in relation to each other as product and process."

This new view of evolution of social networks implies that there can be no intelligent distinction between inherited and acquired characteristics. What evolves is neither genetically encoded nor environmentally acquired, but is ecologically embedded in a social network. There is also no one fixed or pre-given world (a universe), nor is its dynamics simply observed or viewed differentially from a variety of vantage points (a multiverse), but this world itself is continually re-shaped, and re-created by co-evolving social networks of organisms.

Linkage or pleiotropy of "genes" is the rule, not an exception. Organisms are integral and holistic societies, not mechanistic aggregations of separate traits. Therefore, neither DNA sequences, nor genes, organisms, or species, but their entire social networks, coupled and interwoven with their environments, can be the proper units of natural selection and evolution.

This kind of gentle and "velvet" *coup de grâce* to neo-Darwinism and modern synthesis, in all their forms and neoforms, is not to be immediately felt, registered, or even acknowledged. Like the "velvet revolutions" of Eastern Europe, it does not "draw blood," it does not cut off or disconnect "the communists," it does not degrade but firmly establishes new conditions for further growth and evolution. Yet, as Margulis has observed (Mann, 1991), the old *nomenklatura* of neo-Darwinians already hates and resists any autopoietic or Gaian worldview because "it threatens everything they do."

The evolution of paradigms is itself an autopoietic process, and thus inevitably we see how the aged "revolutionaries" are clinging to the old and suddenly ineffective ideas, how they themselves have become conservatives, and how they individually resist the new interpretations of their younger colleagues, often without realizing that their collective time has passed.

CONCLUSION

> When I began my work I felt that I was nearly alone in working on the evolutionary formation of such highly complex self-maintaining orders. Meanwhile, researches on this kind of problem—under various names, such as autopoiesis, cybernetics, homeostasis, spontaneous order, self-organization, synergetics, systems theory, and so on—have become so numerous…
>
> (F.A.Hayek, 1988)

Living systems, i.e., cells, organisms, groups, and species, are social systems. Their interaction forms the entire terrestrial biosphere or Gaia, a social system akin to the unified organism of a living cell, which itself is a social system of its constitutive organelles.

Connecting different species into a coherent, interactive, and self-organizing system cannot happen without death and dying—the fuel of environmental adaptation. The natural death of species does not signal maladaptability of the species, but harmony, adaptability, and systemic perseverance of the social network of species. Death is a cosmological event—the most exquisite assurance of life yet to be. At one point, individuals of all species receive, by waves on the shore, sound of the wind, or with radio telescopes, the exquisite, life-sustaining message: "Now, now it would be indecent not to die."

Harmony and fitness does not imply dominance or competitive advantage but intimate coupling with the environment through all-embracing communication. Nature, as a social system, is replete with communication channels of great variety and subtlety. All life on earth (and most likely interstellar too) is interconnected through internal and external harmonies, often unnoticed or ignored by linear science.

The connexins of cells, dances of bees, odors of fire ants, allochemicals of Douglas firs, and the language of humans are only the hints, only the shy peepholes into the veiled mysteries of life—the promises of science still to come.

NOTES

1 In this sense, talking about, e.g., "social insects" is inadequate as all insects—and also all other organisms—must be social by virtue of their existence.

2 Holistic here does not coincide with the popular "wholistic" as the opposite or the complement to reductionism or atomism. J.C.Smuts's holism (Smuts, 1926) is based on the essential circularity of autopoietic systems: A whole is a unity of parts that affects the interactions of those parts. There can be no parts apart from the whole, and the whole cannot be contemplated apart from its parts: the whole is the parts.

3 In fact a very old (since 1896) and mostly exhausted paradigm (or paradigmatic aberration), fatally unable to explain even the prevalence of stasis in the fossil record or how one species could evolve from another.

4 It is well appreciated that using mere words (especially those loaded with ancient meanings), to express holistic or self-organizational concepts is quite inadequate. This is why the new field of computer simulated patterns of artificial life (AL), if not quickly monopolized by elites of computer hackers, could become so important; it could create a new, wordless language of concepts of complexity.

5 This topological notion of "separation" still persists in some theories of systems, see, e.g., Jessie L.Miller and James Grier Miller (1992), "The Boundary" (*Behavioral Science* 37:23–38): A living system's boundary is a region at its perimeter that separates the system from its environment.

6 The food moving through the mouth and the digestive tube is not necessarily "inside" the body, but remains "outside," in the "captured" or "enveloped" environment of the body torus. The same holds true for all other "boundary" organs; there is no inside or outside, and boundary does not separate anything, except in the human observer's mind.

7 This analogy was first suggested by the British geneticist Sydney Brenner.

8 A promising start could be made by learning to properly pronounce the term apoptosis, meaning "falling from the trees," coined by Andrew Wyllie of Edinburgh.

9 The index of this remarkable text does not contain any references to autopoiesis, Maturana, or artificial life (AL). Yet it refers quite profusely to Abhidharma, Madhyamika, Mahayana, and Sunyata. This constitutes a profound enigma: the book clearly builds upon or motivates the former, while being profoundly irrelevant to the latter.

REFERENCES

Bata, T. (1992) *Knowledge in Action: The Bata System of Management,* IOS Press: Amsterdam.

Cochran, M. *et al.* (eds) (1990) *Extending Families,* Cambridge University Press: Cambridge.

Edelman, G.M. (1988) *Topobiology,* Basic Books: New York.

—— (1992) *Bright Air, Brilliant Fire,* Basic Books: New York.

Eldredge, N. (this volume) "Ultra-Darwinian explanation and the biology of social systems."

Garfinkel, A. (1987) "The slime mold dictyostelium as a model of self-organization in social systems," in *Self-Organizing Systems: The Emergence of Order,* ed. F.Eugene Yates, Plenum Press: New York, 181–212.

Haken, H. (this volume) "Synergetics as a bridge between the natural and social sciences."

Hamada, K. and Monden, Y. (1989) "Profit management at Kyocera Corporation: The amoeba system," in Y.Monden and M.Sakurai (eds), *Japanese Management Accounting,* Productivity Press: Cambridge, MA, 197–210.

Hayek, F.A. (1975) "Kinds of order in society," *Studies in Social Theory* 5, Institute for Humane Studies: Menlo Park, California.

—— (1988) *The Fatal Conceit,* University of Chicago Press: Chicago.

Khalil, E.L. (1990) "Rationality and social labor in Marx," *Critical Review* 4(1–2): 239–265.

Klir, G.J., Hufford, K.D. and Zeleny, M. (1988) "Osmotic growths: A challenge to systems science," *International Journal of General Systems* 14(1): 5–9.

Langton, C.G. (1989) "Artificial life," in *Artificial Life: The Proceedings of an Interdisciplinary Workshop on the Synthesis and Simulation of Living Systems,* ed. C.Langton, Vol. VI, Santa Fe Institute Studies in the Sciences of Complexity Series: Addison-Wesley, 1–47.

Leduc, S. (1911) *The Mechanism of Life,* Rebman: London.

Lewontin, R. (1983) "The organism as the subject and object of evolution," *Scientia* 118: 63–82.

Mackay, C. (1849) *Memoirs of Extraordinary Popular Delusions,* Richard Bentley: London.

Mann, C. (1991) "Lynn Margulis: science's unruly earth mother," *Science* 252, 19 April: 378–381.

Marais, E.N. (1970) *The Soul of the White Ant,* Human & Rousseau: Pretoria.

Mathews, J. (1992) *TCG: Sustainable Economic Organisation Through Networking,* UNSW Studies in Organisational Analysis and Innovation, No. 7, July.

Miller, J.L. and Miller, J.G. (1992) "The boundary," *Behavioral Science* 37(1): 23–38.

Minsky, M. (1986) *The Society of Mind,* Simon & Schuster: New York.

Smuts, J.C. (1926) *Holism and Evolution,* Macmillan: New York.

Topoff, H. (ed.) (1981) *Animal Societies and Evolution,* W.H.Freeman & Co.: San Francisco, CA.

Varela, F.J., Maturana, H.R. and Uribe, R. (1974) "Autopoiesis: The organization of living systems, its characterization and a model," *Biosystems* 5: 187–196.

Varela, F.J., Thompson, E. and Rosch, E. (1991) *The Embodied Mind,* MIT Press: Cambridge, MA.

Zeleny, M. (1978) "APL-autopoiesis: Experiments in self-organization of complexity," *Progress in Cybernetics and Systems Research* 3: 65–84.

—— (ed.) (1980) *Autopoiesis, Dissipative Structures, and Spontaneous Social Orders,* Westview Press: Boulder, Colorado.

—— (ed.) (1981) *Autopoiesis: A Theory of Living Organization,* North-Holland: New York.

—— (1985) "Spontaneous social orders," in *The Science and Praxis of Complexity,* The United Nations University: Tokyo, 312–328; *General Systems* 11(2): 117–131; (1986) "Les ordres sociaux spontanés," in *Science et pratique de la complexité,* Actes du colloque de Montpellier, May 1984, IDATE/UNU, La Documentation Française: Paris, 357–378.

—— (1987) "Cybernetyka," *International Journal of General Systems* 13: 289–294. Also: (1990) "Trentowski's cybernetyka," in *Advances in Systems, Control and Information Engineering*, Pergamon Press: Elmsford, NY.

—— (1988a) "Tectology," *International Journal of General Systems* 14: 331–343.

—— (1988b) "La grande inversione: Corso e ricorso dei modi di vitaumani," in *Physis: abitare la terra,* ed M.Ceruti and E.Laszlo, Feltrinelli: Milan, 413–441.

—— (1988c) "The Bata-system of management: Managerial excellence found," *Human Systems Management* 7(3): 213–219.

—— (1991) "Spontaneous social orders," *in A Science of Goal Formulation: American and Soviet Discussions of Cybernetics and Systems Theory,* ed S.A.Umpleby and V.N. Sadovsky, Hemisphere Publishing Corp.: Washington, DC, 133–150.

Zeleny, M. and Hufford, K.D. (1991) "All autopoietic systems must be social systems," *Journal of Social and Biological Structures* 14(3): 311–332.

—— (1992) "The application of autopoiesis in systems analysis: Are autopoietic systems also social systems?" *International Journal of General Systems* (to appear).

Zeleny, M., Klir, G.J. and Hufford, K.D. (1989) "Precipitation membranes, osmotic growths and synthetic biology," in *Artificial Life: The Proceedings of an Interdisciplinary Workshop on the Synthesis and Simulation of Living Systems,* ed. C. Langton, Vol. VI, Santa Fe Institute Studies in the Sciences of Complexity Series: Addison-Wesley, 125–139.