



CYBERNETICS FORUM

THE PUBLICATION OF THE AMERICAN SOCIETY FOR CYBERNETICS

SUMMER/FALL 1981

VOLUME X

No. 2 and 3

A SPECIAL ISSUE DEVOTED TO AUTOPOIESIS

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SUBSCRIPTION RATES:
ASC Cybernetics Forum
Domestic \$45.00 per year
Foreign \$50.00 per year

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Foreword by the Special-Issues Editor

With this issue, *Cybernetics Forum* assumes a new responsibility. Rather than publishing original articles exclusively, an effort will be made to bring together and to organize cybernetic contributions to knowledge that are scattered throughout numerous and often hard-to-find journals. We recognize that the emphasis on the "one cycle" mass dissemination of newly written articles, which is built into the tradition of journalism, sold to readers as a value and favored by copyright laws, may not promote quality. In contrast, we believe that the aim of furthering cybernetic insights might be better served by recycling articles from time to time whose ideas are prevented from bearing fruit because they appear in obscure journals, by providing access to relevant literature through the publication of selected bibliographies, and by publishing overviews of particular areas of research and theoretical development.

Individually, these issues of *Cybernetics Forum* might be used as mini-textbooks in classes on

cybernetics, systems theory and as reference works in disciplines in which such ideas are applied. Collectively they serve to organize and further develop ideas, to define important issues, and to outline fruitful avenues for research. We also hope that these issues will provide the reader with the stepping stones for intellectual growth.

The issue before us is on *autopoiesis*. The idea is barely a decade old, has emerged in various intellectual domains, especially in biology, and is now in the process of becoming a new paradigm. It promises profoundly new insights in the social sciences, has tremendous philosophical implications, and will change our perspective on our worldview and on ourselves. Other topics being considered for future issues are self-organization, evolution, and management.

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Autopoiesis Today

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Introduction

Most biological and social systems are relatively invariant manifestations of internal material changes evoked by processes of self-production. For example, the entire macromolecular population of components of a biological cell is renewed about 10^4 times during its life time. Yet, throughout this staggering turnover of matter, the cell maintains its distinctiveness, cohesiveness and relative autonomy. The maintenance of organizational unity and wholeness, under conditions of continuous or periodic disassembly and rebuilding, creation and decimation, or production and consumption of the components of this unity is called *autopoiesis*.

The biological cell is not the only form of reality that displays this capability. All living systems are autopoietic in this sense. The organization of some social forms (ant colonies, human groupings, large cities, ideologies) is also primarily determined from within, through the interaction of their continuously replaced components, rather than from the outside through feedback from their environment. Even the organization of the central nervous system is to a large extent spontaneous ("automatic"), or indigenous and independent of sensory feedback. The environment of living systems may perturb or modify their internal processes, and it may affect their components, but it cannot fully explain their organization.

The input-output paradigm of the old (Wienerian) cybernetics provides for the description of systems as externally driven "black boxes" and this is adequate for understanding mechanical devices and systems of interest to engineering. But the application of this paradigm to living and social systems has been intellectually dissatisfying, misleading, and inhibitive of the recognition of those organizational features that make such systems living or social.

The interest in autopoietic organization requires no justification. The paradigm provides new insights into old phenomena and has profound implications for biology and the social sciences. We learn that phenomena of self-organization, reproduction, heredity, evolution and even learning are not primary processes but derived manifestations of autopoiesis. We begin to understand that DNA does not simply order a chaotic mass but that it interacts with self-ordered cells and

large assemblies. It becomes more and more transparent why, for millions of years, species have retained their defining characteristics, the best explanation of which lies in their internal processes. We start to comprehend the resilience and adaptability of social systems, their spontaneous and persisting self-production and material renewal, and their unyielding to social engineering manipulations. Autonomy, one of the most important properties of autopoietic organizations, has become a politically important value for the individual as well as for various levels of social organizations.

Because of its paradigmatically different nature, autopoiesis cannot be easily compared with the traditional input-output control approach. It is based on different premises and presuppositions and it offers a different view of reality. Only experience will tell us how powerful the autopoietic viewpoint is; the time required to reach such a resolution is bound to be substantial. Even if ultimately abandoned in favor of other approaches, the alternative paradigms can only benefit from the challenging encounters with autopoiesis. Our view of the world, especially of living beings and social systems, can certainly never go back to what it was before the processes of autopoiesis became recognizable and penetrable.

The Papers

This issue of *Cybernetics Forum* introduces the reader to the idea of autopoiesis through the three key articles. These have appeared in rather different journals but still can be considered to have ignited exciting developments whose ends are not yet in sight. The three articles are mostly self-explanatory; they are presented in the chronological order of their original published appearance. The reader is encouraged to proceed directly with the papers and then return to the following overview, which is intended to provide additional information.

The first paper, by Varela, Maturana and Uribe, represents the original exposition of autopoiesis as it appeared in *BioSystems* in 1974. It contains many introductory definitions and formulations of autopoiesis, reports some computational experience with a simulation model of autopoiesis, and provides a verbal descrip-

tion of the model. In the next article, published in the *Journal of Man-Machine Studies* in 1975, Maturana reveals the philosophical richness of autopoiesis through his discussion of the nervous system, concepts of structural coupling, ontogeny and evolution, and presents some bold excursions into the linguistic domain. The third article appeared in *General Systems* in 1977. It contains a formal model of autopoiesis, extensive results (autopoietic rhythms, cellular division, morphology controls, etc.), as well as the initial notions of social autopoiesis.

Autopoiesis and Related Research

Of course, autopoiesis is not the only approach employed in the study of holistically emerging, self-organizing, and spontaneously generated phenomena. *Order by fluctuation*, underlying the emergence and evolution of dissipative structures, is now being studied via non-equilibrium thermodynamics (see for example Nicolis and Prigogine, 1977). Theories of self-organizing *hypercycles* of catalytic synthesis of complex nucleic acids and proteins are still being advanced by Eigen and Schuster (1979). There is even a renewed interest in the rules of conduct and *spontaneous social orders* of von Hayek (1967). But autopoiesis, and its more general notion of *organizational closure*, appear capable of addressing all of the above phenomenological domains.

Kenneth E. Boulding (1981) reacted to his own encounter with autopoiesis by observing that its pioneers, like Columbus' three boats, probably thought they were heading for the Indies, that mysterious, still largely unknown, though spicy realm of human knowledge that studies the overwhelmingly mysterious and complex phenomenon of life. What they may well have sighted is a whole new continent, which no Amerigo has yet named, but the hazy outlines of which are now visible to the early explorers. This is nothing less than the study of the whole developmental process of the universe, that is, the general theory of evolution.

Boulding's vision seems to reflect that research scattered over various domains is slowly forming a new system of interlocking ideas which crosses disciplinary boundaries. The bibliography presented here is intended to allow the interested reader to recapture this excitement for himself and to develop his own perspective for the process. To broaden this context of understanding a few related works must be highlighted.

The recent papers by Goguen and Varela (1979) and by Faucheux and Makridakis (1979), go a long way towards presenting and explaining the control/autonomy dilemma of choice. New extensions as well as critical evaluations of autopoiesis are published in *Autopoiesis: A Theory of Living Organization*. Challenging applications, ranging from molecular biology to socio-economic systems, are collected to *Autopoiesis, Dissipative Structures, and Spontaneous Social Orders*. The

original monograph of Maturana and Varela from 1973 has finally been published in English as *Autopoiesis and Cognition*. There is a renewed interest in exploring the historical roots of cybernetics and general systems theories. Several "paradigms lost" are being resurrected, see for example Zeleny (1979), and new histories of these fields are likely to be written. Stafford Beer's soul-searching "Preface to Autopoietic Systems" (1980) should not be missed. Paul A. Weiss, who has used the systems approach in biology since 1925, and whose writings are dominated by autopoietic thinking, received the National Medal of Science in 1980. There is even some obvious fascination with the metaphoric beauty of the term "autopoiesis," as for example in the recent book by the late Erich Jantsch (1980).

Autopoiesis then, to paraphrase Boulding, is truly an idea whose time has come.

Bibliography of Autopoiesis

The following is a rather short selection of only those works which deal with autopoiesis as their main focus of attention. A large number of writings either referring to autopoiesis or briefly commenting upon it were not included; the reader can trace them quite easily from the references provided within the works listed here:

Books and monographs

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Computer Modeling of Autopoiesis

There is now available an interactive modeling package, entitled *APL-Autopoiesis*, suitable for research experimentation with self-organizing systems as well as for game, educational and instructional applications. It is written in the APL language and is fully equipped with special purpose subprograms. The user is allowed to create and implement his own programs and variations through an unlocked APL control program AUTO.

The system is available in one APL workspace (the minimum workspace size is 64K) on an 800 bpi, 9-track non-labeled magnetic tape. The tape is created by the IBM utility DQCEU00, and has the external label AUTOV2. The blocksize is 4000 bytes.

APL-Autopoiesis features print control, statistics plot control, multiple catalysts, production control, link movement control, time limit control, neighborhood control, interaction control, enclosure check control, moving catalysts, print timing control, etc., allowing the user to model desired situations or play interactive competitive games.

User's Manual and leasing/buying information is available from:

COMPUTING AND SYSTEMS CONSULTANTS, Inc.
P.O. Box 1551
Binghamton, NY 13902
U.S.A.

The best way to appreciate and understand the dynamics and the continuous structural transformations of an autopoietic system is through a transcription of the computer output on a video-tape. Autopoiesis can then be observed as a continuous "film" rather than a series of slides. This is now available on SONY videocassette, U-matic, KC-30, in five colors and accompanied by sound. The experience of viewing the emergence and functioning of an autopoietic system through this medium is quite fascinating. It also further underlines the vast potential role the computers can play in the study of living systems.

Autopoiesis Interest Group

The growing number of scientists interested in general aspects of self-organization, autopoiesis, and order through fluctuation has prompted the initiation of "the List" of such persons from a large variety of disciplines.

The purpose of this grouping is to exchange information, maintain and update the relevant literature, and encourage more vigorous discussion across disciplines and across paradigms.

Further information is available from:
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The Netherlands

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Autopoiesis: The Organization of Living Systems, Its Characterization and a Model

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We formulate the organization of living organisms through the characterization of the class of autopoietic systems to which living things belong. This general characterization is seen at work in a computer simulated model of a minimal case satisfying the conditions for autopoietic organization.

1. Introduction

Notwithstanding their diversity, all living systems must share a common organization which we implicitly recognize by calling them "living". At present there is no formulation of this organization, mainly because the great developments of molecular, genetic and evolutionary notions in contemporary biology have led to the overemphasis of isolated components, e.g. to consider reproduction as a necessary feature of the living organization and, hence, not to ask about the organization which makes a living system a whole, autonomous unity that is alive regardless of whether it reproduces or not. As a result, processes that are history dependent (evolution, ontogenesis) and history independent (individual organization) have been confused in the attempt to provide a single mechanistic explanation for phenomena which, although related, are fundamentally distinct.

We assert that reproduction and evolution are not constitutive features of the living organization and that the properties of a unity cannot be accounted for only through accounting for the properties of its components. In contrast, we claim that the living organization can only be characterized unambiguously by specifying the network of interactions of components which constitute a living system as a whole, that is, as a "unity". We also claim that all biological phenomenology, including reproduction and evolution, is secondary to the establishment of this unitary organization. Thus, instead of asking "What are the necessary properties of the components that make a living system possible?"

we ask "What is the necessary and sufficient organization for a given system to be a living unity?" In other words, instead of asking what makes a living system reproduce, we ask what is the organization reproduced when a living system gives origin to another living unity? In what follows we shall specify this organization.

2. Organization

Every unity can be treated either as an unanalyzable whole endowed with constitutive properties which define it as a unity, or else as a complex system that is realized as a unity through its components and their mutual relations. If the latter is the case, a complex system is defined as a unity by the relations between its components which realize the system as a whole, and its properties as a unity are determined by the way this unity is defined, and not by particular properties of its components. It is these relations which define a complex system as a unity and constitute its organization. Accordingly, the same organization may be realized in different systems with different kinds of components as long as these components have the properties which realize the required relations. It is obvious that with respect to their organization such systems are members of the same class, even though with respect to the nature of their components they may be distinct.

3. Autopoietic Organization

It is apparent that we may define classes of systems (classes of unities) whose organization is specifiable in terms of spatial relations between components. This is the case of crystals, different kinds of which are defined only by different matrices of spatial relations. It is also apparent that one may define other classes of systems whose organization is specifiable only in terms of relations between processes generated by the interactions of components, and not by spatial relations between these components. Such is the case of mechanistic systems in general, different kinds of (relations) of processes. In particular this is the case of living systems whose organization as a subclass of mechanistic systems we wish to specify.

The autopoietic organization is defined as a unity by a

network of productions of components which (i) participate recursively in the same network of productions of components which produced these components, and (ii) realize the network of productions as a unity in the space in which the components exist. Consider for example the case of a cell: it is a network of chemical reactions which produce molecules such that (i) through their interactions generate and participate recursively in the same network of reactions which produced them, and (ii) realize the cell as a material unity. Thus the cell as a physical unity, topographically and operationally separable from the background, remains as such only insofar as this organization is continuously realized under permanent turnover of matter, regardless of its changes in form and specificity of its constitutive chemical reactions.

4. Autopoiesis and Allopoiesis

The class of systems that exhibit the autopoietic organization, we shall call autopoietic systems.

Autonomy is the distinctive phenomenology resulting from an autopoietic organization: the realization of the autopoietic organization is the product of its operation. As long as an autopoietic system exists, its organization is invariant; if the network of productions of components which define the organization is disrupted, the unity disintegrates. Thus an autopoietic system has a domain in which it can compensate for perturbations through the realization of its autopoiesis, and in this domain it remains a unity.

In contradistinction, mechanistic systems whose organization is such that they do not produce the components and processes which realize them as unities and, hence, mechanistic systems in which the product of their operation is different from themselves, we call allopoietic. The actual realization of these systems, therefore, is determined by processes which do not enter in their organization. For example, although the ribosome itself is partially composed of components produced by ribosomes, as a unity it is produced by processes other than those which constitute its operation. Allopoietic systems are by constitution non-autonomous insofar as their realization and permanence as unities is not related to their operation.

5. Autopoiesis: The Living Organization

The biological evidence available today clearly shows that living systems belong to the class of autopoietic systems. To prove that the autopoietic organization is the living organization, it is then sufficient to show, on the other hand, that an autopoietic system is a living system. This has been done by showing that for a system to have the phenomenology of a living system suffices that its organization be autopoietic (Maturana and Varela, 1973).

Presently, however, it should be noticed that in this characterization, reproduction does not enter as a requisite feature of the living organization. In fact, for

reproduction to take place there must be a unity to be reproduced: the establishment of the unity is logically and operationally antecedent to its reproduction. In living systems the organization reproduced is the autopoietic organization, and reproduction takes place in the process of autopoiesis; that is, the new unity arises in the realization of the autopoiesis of the old one. Reproduction in a living system is a process of *division* which consists, in principle, of a process of fragmentation of an autopoietic unity with distributed autopoiesis such that the cleavage separates fragments that carry the same autopoietic network of production of components that defined the original unity. Yet, although self-reproduction is not a requisite feature of the living organization, its occurrence in living systems as we know them is a necessary condition for the generation of a historical network of successively generated, not necessarily identical, autopoietic unities, that is, for evolution.

6. A Minimal Case: The Model

We wish to present a simple embodiment of the autopoietic organization. This model is significant in two respects: on the one hand, it permits the observation of the autopoietic organization at work in a system simpler than any known living system, as well as its spontaneous generation from components; on the other hand, it may permit the development of formal tools for the analysis and synthesis of autopoietic systems.

The model consists of a two-dimensional universe where numerous \circ elements ("substrate"), and a few \star ("catalysts") move randomly in the spaces of a quadratic grid. These elements are endowed with specific properties which determine interactions that may result in the production of other elements \square ("links") with properties of their own and also capable of interactions ("bonding"). Let the interactions and transformations be as follows:

SCHEMA I

[1] Composition: $\star + 2 \circ \rightarrow \star + \square$

[2] Concatenation:
(Bonding) $\underbrace{\square - \square - \dots - \square}_n + \square \rightarrow \underbrace{\square - \square - \dots - \square}_{n+1}$
 $n = 1, 2, 3, \dots$

[3] Disintegration: $\square \rightarrow 2 \circ$

Interaction [1] between the catalyst \star and two substrate elements $2 \circ$ is responsible for the composition of an unbonded link \square . These links may be bonded through Interaction [2] which concatenates these bonded links to unbranched chains of \square . A chain so produced may close upon itself, forming an enclosure which we assume to be penetrable by the \circ 's, but not for \star . Disintegration (Interaction [3]) is assumed to be independent of the state of links \square , i.e., whether they are free or bound, and can be viewed either as a spon-

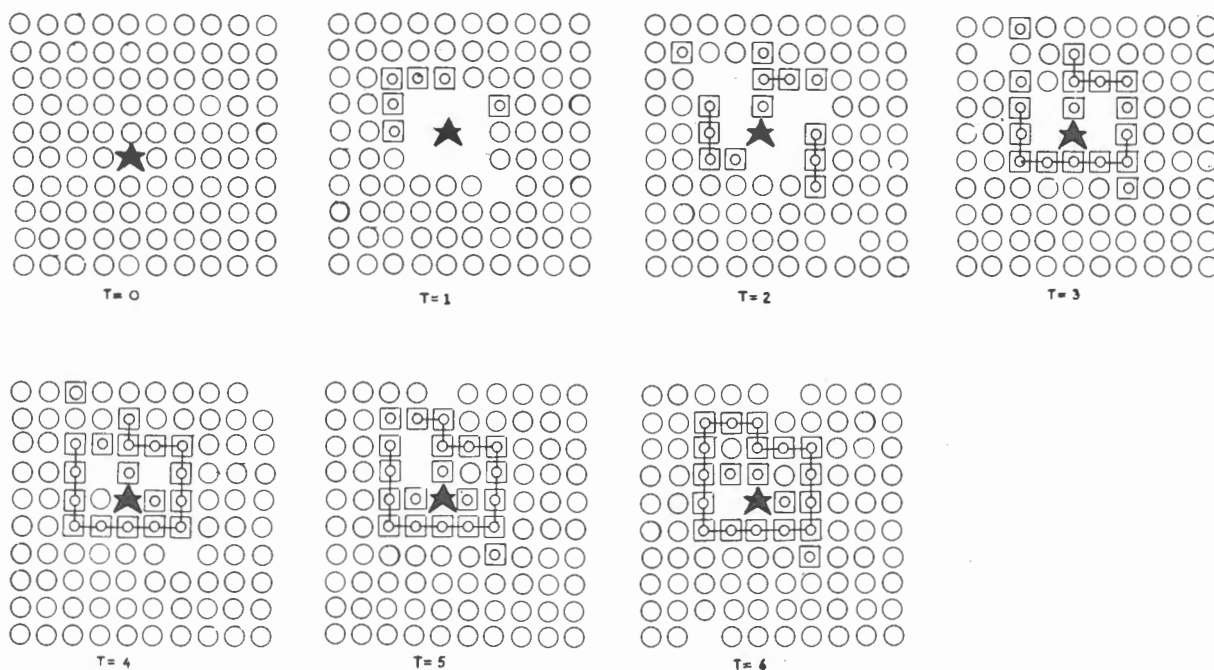


Fig. 1. The first seven instants (0→6) of one computer run, showing the spontaneous generation of an autopoietic unity. Interactions between substrate \circ and catalyst \star produce chains of bonded links \square , which eventually enclose the catalyst, thus closing a network of interactions which constitutes an autopoietic unity within this universe.

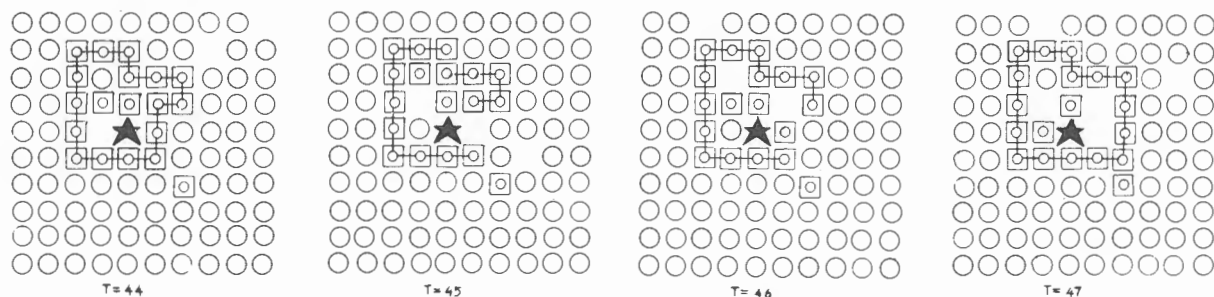


Fig. 2. Four successive instants (44-47) along the same computer run (Fig. 1), showing compensation in the boundary broken by spontaneous decay of links. Ongoing production of links re-establishes the unity under changes of form and turnover of components.

taneous decay or as a result of a collision with a substrate element \circ .

In order to visualize the dynamics of the system, we show two sequences (Figures 1 and 2) of successive stages of transformation as they were obtained from the print-out of a computer simulation of this system.*

If an \square -chain closes on itself enclosing an element \star (Fig. 1), the \square 's produced within the enclosure by interaction [1] can replace in the chain, via [2], the elements \square that decay as a result of [3] (Fig. 2). In this manner, a unity is produced which constitutes a network of productions of components that generate and participate in the network of productions that produced

these components by effectively realizing the network as a distinguishable entity in the universe where the elements exist. Within this universe these systems satisfy the autopoietic organization. In fact, element \star and elements \circ produce element \square in an enclosure formed by a bidimensional chain of \square 's; as a result the \square 's produced in the enclosure replace the decaying \square 's of the boundary, so that the enclosure remains closed for \star under continuous turnover of elements, and under recursive generation of the network of productions which thus remains invariant (Figs. 1 and 2). This unity cannot be described in geometric terms because it is not defined by the spatial relations of its components. If one stops all the processes of the system at a moment in which \star is enclosed by the \square -chain, so that spatial relations between the components become fixed, one indeed has a system definable in terms of spatial relations, that is, a crystal,

*Details of computation are given in the Appendix. To facilitate appreciation of the developments, Fig. 1 and 2 are drawn from the print-outs with change of symbols used in the computations.

but not an autopoietic unity.

It should be apparent from this model that the processes generated by the properties of the components (Schema I) can be concatenated in a number of ways. The autopoietic organization is but one of them, yet it is the one that by definition implies the realization of a dynamic unity. The same components can generate other, allopoietic organizations; for example, a chain which is defined as a sequence of \square 's, is clearly allopoietic since the production of the components that realize it as a unity do not enter into its definition as a unity. Thus, the autopoietic organization is neither represented nor embodied in Schema I, as in general no organization is represented or embodied in the properties that realize it.

7. Tessellation and Molecules

In the case described, as in a broad spectrum of other studies that can generically be called tessellation automata (von Neumann, 1966; Gardner, 1971), the starting point is a generalization of the physical situation. In fact, one defines a space where spatially distinguishable components interact, thus embodying the concatenation of processes which lead to events among the components. This is of course what happens to the molecular domain, where autopoiesis as we know it takes place. For the purpose of explaining and studying the notion of autopoiesis, however, one may take a more general view as we have done here, and revert to the tessellation domain where physical space is replaced by any space (a two-dimensional one in the model), and molecules by entities endowed with some properties. The phenomenology is unchanged in all cases: the autonomous self-maintenance of a unity while its organization remains invariant in time.

It is apparent that in order to have autopoietic systems, the components cannot be simple in their properties. In the present case we required that the components have specificity of interactions, forms of linkage, mobility and decay. None of these properties are dispensable for the formation of this autopoietic system. The necessary feature is the presence of a boundary which is produced by a dynamics such that the boundary creates the conditions required for this dynamics. These properties should provide clues to the kind of molecules we should look for in order to produce an autopoietic system in the molecular domain. We believe that the synthesis of molecular autopoiesis can be attempted at present, as suggested by studies like those on microspheres and liposomes (Fox, 1965; Bangham, 1968) when analyzed in the present framework. For example: a liposome whose membrane lipidic components are produced and/or modified by reactions that take place between its components, only under the conditions of concentration produced within the liposome membrane, would constitute an autopoietic system. No experiments along these lines have been carried out, although they are potential keys for the origin of living systems.

8. Summary

We shall summarize the basic notions that have been developed in this paper:

A. There are mechanistic systems that are defined as unities by a particular organization which we call autopoietic. These systems are different from any other mechanistic system in that the product of their operation as systems thus defined is necessarily always the system itself. If the network of processes that constitutes the autopoietic system is disrupted, the system disintegrates.

B. The phenomenology of an autopoietic system is the phenomenology of autonomy: all changes of state (internal relations) in the system that takes place without disintegration are changes in autopoiesis which perpetuate autopoiesis.

C. An autopoietic system arises spontaneously from the interaction of otherwise independent elements when these interactions constitute a spatially contiguous network of productions which manifests itself as a unity in the space of its elements.

D. The properties of the components of an autopoietic system *do not* determine its properties as a unity. The properties of an autopoietic system (as is the case for every system) are determined by the constitution of this unity, and are, in fact, the properties of the *network* created by, and creating, its components. Therefore, to ascribe a determinant value to any component, or to any of its properties, because they seem to be "essential", is a semantic artifice. In other words, all the components, and the components' properties, as well as the circumstances which permit their productive interactions, are necessary when they participate in the realization of an autopoietic network, and none is determinant of the constitution of the network or of its properties as a unity.

9. Key

The following is a six-point key for determining whether or not a given unity is autopoietic:

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 transformations 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, *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.

Acknowledgement

The authors wish to express their gratitude to the members of the Biological Computer Laboratory of the University of Illinois, Urbana, particularly to Richard Howe, Heinz Von Foerster, Paul E. Weston and Kenneth L. Wilson, for their continuous encouragement, discussions, and help in clarifying and sharpening the presentation of our notions.

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APPENDIX

Conventions

We shall use the following alphanumeric symbols to designate the elements referred to earlier:

Substrate:	○ → S
Catalyst:	* → K
Link:	⊠ → L
Bonded link:	⊠-⊠ → BL

the two dimensional array of positions, and with production and disintegration of the L components out of and back into the substrate S's. The rules by which L components bond to form a boundary complete the algorithm.

The "space" is a rectangular array of points, individually addressable by their row and column posi-

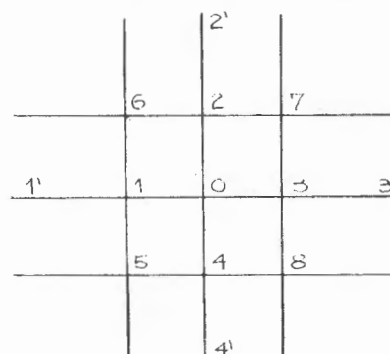


FIGURE 3. Designation of coordinates of neighboring spaces with reference to a space with designation "0".

tions within the array. In its initial state this space contains one or more catalyst molecules K with all remaining positions containing substrate S.

In both the motion and production phases, it is necessary to make random selections among certain sets of positions neighboring the particular point in the space at which the algorithm is being applied. The numbering scheme of Figure 3 is then applied; with location 0 in the figure being identified with the point of application (of course, near the array boundaries, not all of the neighbor locations identified in the figure will actually be found).

Regarding motion, the components are ranked by increasing "mass" as S, L, K. The S's may not displace any other species, and thus are only able to move into "holes" or empty spaces in the grid, though they can pass through a *single* thickness of bonded link BL's to do so. On the other hand the L and K readily displace S's, pushing them into adjacent holes, if these exist, or else exchanging positions with them, thus passing freely through the substrate S. The most massive, K, can similarly displace free L links. However, neither of these can pass through a bonded link segment, and are thus effectively contained by a closed membrane. Concatenated L's, forming bonded link segments, are subject to no motions at all.

Regarding production, the initial state contains no bonded links at all; these appear only as the result of formation from substrate S's in the presence of the catalyst. This occurs whenever two adjacent neighboring positions of a catalyst are occupied by S's (e.g., 2 and 7, or 5 and 4 in Figure 3). Only one L is formed per time step, per catalyst, with multiple possibilities being resolved by random choice. Since two S's are combined to form one L, each such production leaves a new hole in the space, into which S's may diffuse.

The disintegration of L's is applied as a uniform pro-

The algorithm has two principal phases concerned, respectively, with the motion of the components over

bability of disintegration per time step for each L whether bonded or free, which results in a proportionality between failure rate and size of chain structure. The sharply limited rate of "repair", which depends upon random motion of S's through the membrane, random production of new L's and random motion to the repair site, makes the disintegration a very powerful controller of the maximum size for a viable boundary structure. A disintegration probability of less than about .01 per time step is required in order to achieve any viable structure at all (these must contain roughly ten L units at least to form a closed structure with any space inside).

Algorithm

1. Motion, first step
 - 1.1. Form a list of the coordinates of all holes h_i .
 - 1.2. For each h_i , make a random selection, n_i , in the range 1 through 4, specifying a neighboring location.
 - 1.3. For each h_i in turn, where possible move occupant of selected neighboring location in h_i .
 - 1.31. If the neighbor is a hole or lies outside the space, take no action.
 - 1.32. If the neighbor n_i contains a bonded L, examine the location n'_i . If n'_i contains an S, move this S to h_i .
 - 1.4. Bond any moved L, if possible (Rules, 6).
2. Motion, second step
 - 2.1. Form a list of the coordinates of free L's, m_i .
 - 2.2. For each m_i , make a random selection, n_i , in the range 1 through 4, specifying a neighboring location.
 - 2.3. Where possible, move the L occupying the location m_i into the specified neighboring location.
 - 2.31. If location specified by n_i contains another L, or a K, then take no action.
 - 2.32. If location specified by n_i contains an S, the S will be displaced.
 - 2.321. If there is a hole adjacent to the S, it will move into it. If more than one such hole, select randomly.
 - 2.322. If the S can be moved into a hole by passing through bonded links, as in step 1, then it will do so.
 - 2.323. If the S cannot be moved into a hole, it will exchange locations with the moving L.
 - 2.33. If the location specified by n_i is a hole, then L simply moves into it.
 - 2.4. Bond each moved L, if possible.
3. Motion, third step
 - 3.1. Form a list of the coordinates of all K's, c_i .
 - 3.2. For each c_i , make a random selection n_i , in the range 1 through 4, specifying a neighboring location.
 - 3.3. Where possible, move the K into the selected neighboring location.
 - 3.31. If the location specified by n_i contains a BL or another K, take no action.
 - 3.32. If the location specified by n_i contains a free L,

which may be displaced according to the rules of 2.3, then the L will be moved, and the K moved into its place. (Bond the moved L, if possible).

3.33. If the location specified by n_i contains an S, then move the S by the rules of 2.32.

3.34. If the location specified by n_i contains a free L, not movable by rules 2.3, exchange the positions of the K and the L. (Bond L if possible).

3.35. If the location specified by n_i is a hole, the K moves into it.

4. Production

4.1. For each catalyst c_i , form a list of the neighboring positions n_{ij} , which are occupied by S's.

4.11. Delete from the list of n_{ij} all positions for which neither adjacent neighbor position appears in the list (i.e., "1" must be deleted from the list of n_{ij} 's, if neither 5 nor 6 appears, and a "6" must be deleted if neither 1 nor 2 appears).

4.2. For each c_i with a non-null list of n_{ij} , choose randomly one of the n_{ij} , let its value be p_i , and at the corresponding location, replace the S by a free L.

4.21. If the list of n_{ij} contains only one which is adjacent to p_i , then remove the corresponding S.

4.22. If the list of n_{ij} includes both locations adjacent to p_i , randomly select the S to be removed.

4.3. Bond each produced L, if possible.

5. Disintegration

5.1. For each L, bonded or unbonded, select a random real number, d , in the range (0,1).

5.11. If $d > P_d$ (P_d an adjustable parameter of the algorithm), then remove the corresponding L, attempt to re-bond (Rules, 7).

5.12. Otherwise proceed to next L.

6. Bonding

This step must be given the coordinates of a free L.

6.1. Form a list of the neighboring positions n_i , which contains free L's, and the neighboring positions m_i , which contain singly bonded L's.

6.2. Drop from the m_i any which would result in a bond angle less than 90° . (Bond angle is determined as in Figure 4).

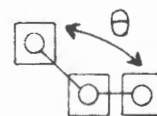


Fig. 4. Definition of "Bond-Angle" θ .

6.3. If there are two or more of the m_i , select two, form the corresponding bonds, and exit.

6.4. If there is exactly one m_i , form the corresponding bond.

6.41. Remove from the n_i any which would now result in a bond angle of less than 90° .

6.42. If there are no n_i , exit.

6.43. Select one of the n_i , form the bond, and exit.

- 6.5. If there are no n_i , exit.
- 6.6. Select one of the n_i , form the corresponding bond, and drop it from the list.
- 6.61. If the n_i list is non-null, execute steps 6.41 through 6.43.
- 6.62. Exit.
7. Rebond
 - 7.1 Form a list of all neighbor positions m_i occupied by singly bonded L's.
 - 7.2 Form a second list, p_{ij} , of pairs of the m_i which can be bonded.
 - 7.3. If there are any p_{ij} , choose a maximal subset and form the bonds. Remove the L's involved from the list m_i .
 - 7.4. Add to the bond m_i any neighbor locations occupied by free L's.
 - 7.5. Execute steps 7.1 through 7.3, then exit.

The Organization of the Living: A Theory of the Living Organization*

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(Received 2 October 1974)

The fundamental feature that characterizes living systems is autonomy, and any account of their organization as systems that can exist as individual unities must show what autonomy is as a phenomenon proper to them, and how it arises in their operation as such unities. Accordingly the following is proposed.

(1) That autonomy in living systems is a feature of self-production (autopoiesis), and that a living system is properly characterized only as a network of processes of production of components that is continuously, and recursively, generated and realized as a concrete entity (unity) in the physical space, by the interactions of the same components that it produces as such a network. This organization I call the autopoietic organization, and any system that exhibits it is an autopoietic system in the space in which its components exist; in this sense living systems are autopoietic systems in the physical space.

(2) That the basic consequence of the autopoietic organization is that everything that takes place in an autopoietic system is subordinated to the realization of its autopoiesis, otherwise it disintegrates.

(3) That the fundamental feature that characterizes the nervous system is that it is a closed network of interacting neurons in which every state of neuronal activity generates other states of neuronal activity. Since the nervous system is a component subsystem in an autopoietic unity, it operates by generating states of relative neuronal activity that participate in the realization of the autopoiesis of the organism which it integrates.

(4) That the autopoietic states that an organism adopts are determined by its structure (the structure of the nervous system included), and that the structure of

the organism (including its nervous system) is at any instant the result of its evolutionary and ontogenic structural coupling with the medium in which it is autopoietic, obtained while the autopoiesis is realized.

(5) That language arises as phenomenon proper to living systems from the reciprocal structural coupling of at least two organisms with nervous systems, and that self-consciousness arises as an individual phenomenon from the recursive structural coupling of an organism with language with its own structure through recursive self-description.

Purpose

My purpose in this article is to present a theory of the organization of living systems as autonomous entities, and a theory of the organization of the nervous system as a closed network of interacting neurons structurally coupled to the living system to whose realization it contributes.

Antecedents

(a) There is no adequate theory of the organization of living systems as individual autonomous unities. There are only descriptions of some of their internal states and of their states of interaction as these appear projected upon the domain of observation and purposeful design of the observer. Thus, reproduction, processing of information or internal hierarchical relations, are described as fundamental constitutive features of the living organization. Yet, at a closer scrutiny, none of these features appears to be exclusive, or definitory of living systems. In fact, reproduction is trivially non-constitutive, even though it is necessary for evolution, because living systems are living systems, whether in reproduction or not, as long as they are "alive". The notion of processing of information represents a way of description of the interactions and changes of state of a system, and as such it is applicable to any possible dynamic system. Finally, the possession of internal hierarchical relations is a feature that an observer can ascribe to any mechanistic system to which he assigns an initial and a final state in its sequential-state transi-

The article first appeared in *International Journal of Man-Machine Studies*, Vol. 7, 1975 published by Academic Press, Inc. (London) Ltd. We appreciate the permission of the publisher to re-typeset the article.

*An earlier version of this paper was presented at the Conference on Biologically Motivated Automata Theory, MacLean, Va., U.S.A., 19-21 June 1974.

tions. The same applies to the nervous system. There is no adequate theory of the nervous system as a neuronal network embedded in an autonomous living unity; there are only descriptions of the state transitions of the nervous system viewed as an input-output system designed for the processing of environmental information. The result of this view is the treatment of the nervous system as an organ through which the organism becomes semantically coupled to its environment, as if the features of the description (semantic relations) were effective operative components in the changes of state of the organism.

(b) It is the aim of many scientists who work in automata theory to model the most unique phenomena generated by living systems such as autonomy, language and self-consciousness. Such an aim, however, cannot be achieved in the absence of a theory that shows the nature of these phenomena and how they arise in biological systems.

Preliminary Concepts

Observer. An observer is a human being, a person; someone who can make distinctions and specify that which he distinguishes as an entity (a something) different from himself, and can do this with his own actions and thoughts recursively, being always able to operate as if external to (distinct from) the circumstances in which he finds himself. All the distinctions that we handle, conceptually or concretely, are made by us as observers: everything said is said by an observer to another observer.

Unity. A unity is an entity (concrete or conceptual) separated from a background by a concrete or conceptual operation of distinction. A unity may be treated as an unanalyzable whole endowed with constitutive properties, or as a composite entity with properties as a unity that are specified by its organization and not by the properties of its components.

Interaction. Whenever two unities, specified by their properties and as a result of the interplay of these properties, appear to modify their relative states in reference to the larger systems in which they are embedded, there is an interaction.

Space. Space is the domain of all the possible relations and interactions of a collection of elements that the properties of these elements define.

Explanation. An explanation is always addressed by an observer to another observer. An explanation is an intended reproduction. A system is explained when the relations which define it as a unity are, either conceptually or concretely, intentionally reproduced. A phenomenon is explained when the processes which generate it are, either conceptually or concretely, intentionally reproduced in a manner that shows that by their operation they generate the phenomenon to be explained. It follows that there are two basic problems that must be solved in any explanation, namely: (a) the distinction and identification of the unity or phenomenon to be explained; and (b) the conceptual or

concrete reproduction, either of the organization of the unity or of the mechanisms and processes that generate the phenomenon to be explained.

Organization. This word comes from the Greek term *οργανον* (organon) that means instrument, and by making reference to the instrumental participation of the components in the constitution of the unity, it refers to the relations between components which define a system as a unity. So, in order to define a system as a unity it is necessary and sufficient to point to its organization. From the cognitive point of view, the organizations of a unity specifies the concept which defines the class of unities to which it belongs.

Structure. This word comes from the latin verb *struere* that means to build, and by making reference to the process of construction as well as to the components of a construct, it refers to the actual components and to the actual relations which these must satisfy in their participation in the constitution of a given unity. An observer may recognize a known system by identifying its components, but an unknown system cannot be defined by pointing to its structure.

Organization and structure, therefore, are not synonyms. The organization of a composite system constitutes it as a unity and determines its properties as such a unity, specifying a domain in which it may interact (and be treated) as an unanalyzable whole. The structure of a composite system determines the space in which it exists and can be perturbed, but not its properties as a unity. An unanalyzable unity can be identified by a concept, but it does not have an organization, nor does it have a structure, it only has properties as a fundamental element that exists in a space which these properties specify. It follows that two spatially separated composite unities may have the same organization but different structures and that a composite unity (system) remains the same only as long as its organization remains invariant: whenever the organization of a unity changes the unity changes, it becomes a different unity; whenever the structure of a unity changes without change in its organization, the unity remains the same and its identity stays unchanged. It also follows that when the organization of a unity is to be explained it is a mistake to reproduce its structure, it is necessary and sufficient to reproduce its organization and, thus produce one of the kind; yet, when a particular unity is to be reproduced, both its organization and its structure must be reproduced.

Furthermore, since a composite unity interacts through the properties of its components, and an unanalyzable one through its constitutive properties as a unity, all interactions between unities, including interactions with the observer (observation), are necessarily structural interactions in the space of the components. Therefore, when an observer refers to the organization of a composite unity, he refers to the relations which realize the concept that defines the class of unities to which the observed composite unity belongs.

State-determined system. A state-determined system whose changes of state, defined as structural changes

without loss of identity (defining organization), are determined by the structure of the system and not by an independent perturbing agent. This is a universal constitutive feature of dynamic systems.

Consensual domain. A consensual domain is a domain of interlocked (intercalated and mutually triggering) sequences of states, established and determined through ontogenic interactions between structurally plastic state-determined systems. A consensual domain can become established only when the plastic interacting systems are homeostatic systems that maintain constant their essential variables through their mutual interactions. Living systems do establish consensual domains through the maintenance of their living organization.

Phenomenological domain. Domain of interactions specified by the properties of the interacting unities, regardless of whether these unities are simple or composite. Therefore, when a unity is defined, through the specification of its organization or by pointing to its properties, a phenomenological domain is defined.

Purpose

After these preliminary considerations, and given that living systems exist and that some of them have a nervous system, the two aims of this article can now be precisely stated as follows.

(a) To explain the organization of living systems by describing the organization that constitutes a system as an autonomous unity that can, in principle, generate *all the phenomenology* proper to living systems if the adequate historical contingencies are given.

(b) To explain the organization of the nervous system by describing the organization that makes a neuronal network, integrated as a component subsystem in an organism, a system that can generate *all the phenomenology* proper to a nervous system.

Theory

AUTOPOIESIS (αὐτοο = self; ποιεῖν = to make)

Living systems are given and they generate a specific phenomenology, the phenomenology of living systems. Therefore, in order to explain living systems it is necessary and sufficient to point to the organization that defines a class of unities that generates a phenomenology indistinguishable from the phenomenology proper to living systems. Such an organization can be described as follows.

There is a class of mechanistic systems in which each member of the class is a dynamic system defined as a unity by relations that constitute it as a network of processes of production of components which: (a) recursively participate through their interactions in the generation and realization of the network of processes of production of components which produced them; and (b) constitute this network of processes of production of components as a unity in the space in which they (the

components) exist by realizing its boundaries.

Such systems I call *autopoietic systems*: the organization of an autopoietic system is the *autopoietic organization*. An autopoietic system that exists in the physical space is a living system (Maturana & Varela, 1973; Varela, Maturana & Uribe, 1974).

As a result of their organization, autopoietic systems operate as homeostatic systems that have their own organization as the critical fundamental variable that they actively maintain constant. In an autopoietic system all its (dynamic) states are states in autopoiesis and lead to autopoiesis. In this sense, autopoietic systems are closed systems, and, as a result of this, all the phenomenology of autopoietic systems is necessarily subservient to their autopoiesis, and a given phenomenon is a biological phenomenon only to the extent to which it involves the autopoiesis of at least one living system.

NERVOUS SYSTEM

The nervous system is given as a network of interacting neurons that generates a phenomenology subservient to the autopoiesis of the organism in which it is embedded. Therefore, in order to explain the nervous system as a system, it is necessary and sufficient to point to the organization that defines a neuronal network that generates a phenomenology indistinguishable from the phenomenology proper to the nervous system as it exists as a constitutive component of an autopoietic system. Such organization can be described as follows.

The nervous system is defined as a unity (that is, as a system) by relations that constitute it as a closed network of interacting neurons such that any change in the state of relative activity of collection of neurons leads to a change in the state of relative activity of other or the same collection of neurons: all states of neuronal activity in the nervous system always lead to other states of activity in the nervous system.

A closed neuronal network does not have input or output surfaces as features of its organization, and although it can be perturbed through the interactions of its components, for it, in its operation as a system, there are only its own states of relative neuronal activity, regardless of what the observer may say about their origin. Given a closed system, inside and outside exist only for the observer who beholds it, not for the system. The sensory and the effector surfaces that an observer can describe in an actual organism, do not make the nervous system an open neuronal network because the environment (where the observer stands) acts only as an intervening element through which the effector and sensory neurons interact completing the closure of the system.

If the observer, either experimentally or conceptually, were to open the nervous system at some synaptic surface, and describe the transfer properties of the system thus obtained in terms of input and output relations, he

would have an open network, but not a nervous system. This is what in fact happens when the observer describes the organism as a system which has independent sensory and effector surfaces for its interactions with the environment: he opens the nervous system and destroys its organization, leaving only an open neuronal network that can be described in terms of hierarchical transfer functions which are relevant only for the descriptive system of references introduced by the observer, who describes the changes of state of the nervous system by mapping them upon the changes of state of the environment (observable medium). As a closed neuronal network, however, the state-determined system that the nervous system is operated by generating relations of neuronal activity determined by its structure, regardless of environmental circumstances. The observable effectiveness that the relations of neuronal activity generated by the nervous system have for the realization of the autopoiesis of the organism under environmental perturbations results from the structural correspondence that actually exists between nervous system and organism, and between these and the medium in which the autopoiesis of the organism is realized.

IMPLICIT REQUIREMENTS

An autopoietic system is a state-determined composite dynamic unity. Therefore, although the characterization of an autopoietic system does not require any statement about the characteristics of the medium in which the autopoiesis is realized, the actual realization of an autopoietic system in the physical space requires of a medium that provides the physical elements that permit the processes of production of components to take place. This medium includes all that is operationally different from the autopoietic unity, that is, all that at some instances may constitute a perturbation, even components of the system itself. It is, then, an implicit constitutive condition for autopoiesis that the autopoietic unity exists in a medium within which it interacts, and within which an observer can see it interchange elements with an environment.

PLASTICITY AND STRUCTURAL COUPLING

The interactions of a composite unity in the space of its components are interactions through its components, that is, are structural interactions. If as a result of a structural interaction the components of a unity, or their relations, change, the structure of the unity changes, and, if these structural changes occur without a change in the organization of the unity, the identity of the unity remains invariant. A unity whose structure can change while its organization remains invariant is a plastic unity, and the structural interactions under which this invariance can be sustained are perturbations. Since the changes of state of an autopoietic

system are determined by its structure, the perturbations under which the autopoietic unity undergoes its changes of state (changes of structure without loss of identity) constitutes only triggering events that couple the sequence of the changes of state of the autopoietic unity to the sequence of the changes of state of the medium that constitute the perturbations. Given that it is a constitutive feature of an autopoietic unity to homeostatically maintain invariant its organization under conditions of structural change, the realization of the autopoiesis of a plastic autopoietic unity under conditions of perturbations generated by a changing medium, necessarily results either in the establishment in the autopoietic unity of a structure that can generate specific changes of state that can be triggered by specific perturbing changes of state of the medium, or in its disintegration. The result of the establishment of this dynamic structural correspondance, or *structural coupling*, is the effective spatio-temporal correspondance of changes of state of the organism with the recurrent changes of state of the medium while the organism remains autopoietic.

The same arguments can be applied to the nervous system whose organization must be invariant, but whose structures needs not be so and may be plastic, with a dynamic of structural change coupled to the dynamic of structural change of other systems such as the organism which it integrates, and through this, to the medium in which this exists. In fact, if the structure of the nervous system changes, the domain of the possible states of neuronal activity of the nervous system, and, hence, the domain of the possible behavioural states of the organism itself, change too. Therefore, if as a result of the structural changes of the nervous system the organism can go on in autopoiesis, the new nervous system's structure obtained may constitute the basis for a new structural change which may also permit the organism to go on in autopoiesis. In principle, this process can be recursively repeated endlessly along the life of an organism, and generate a process of continuous structural transformation that specifies the relations of neuronal activity that the nervous system generates in its participation in the autopoiesis. The consequences of this structural coupling are threefold:

(a) while the autopoiesis lasts, the changing structure of the nervous system is necessarily that which generates the state of relative neuronal activity that participate in the continued autopoiesis of the organism in the medium in which it exists;

(b) while the autopoiesis lasts, the nervous system operates as an homeostatic system that generates relations of neuronal activity that are subordinated to and determined by the actual realization of the autopoiesis of the organism which it integrates;

(c) while the autopoiesis lasts, the structural coupling of the nervous system to the organism and medium, revealed as a spatio-temporal correspondance between the changes of state of the organism and the changes of state of the medium (recursively including the organism and the nervous system itself), appear to an observer as

a semantic coupling.

In general, then, the reciprocal structural coupling of the organism and nervous system, and their simultaneous structural coupling to the medium in which the autopoiesis is realized, are necessary consequences of the continued autopoiesis of the organism when these systems have plastic structures.

ONTOGENY AND EVOLUTION

The history of structural changes without loss of identity in an autopoietic unity is its ontogeny. The coupling of the changing structure of an autopoietic unity to the changing structure of the medium in which it exists, is ontogenic adaptation. The ontogenic adaptation of the nervous system is learning; or, in other words, given that the structure of the nervous system is plastic and that the nervous system is subservient to the autopoiesis of the organism which it integrates, the determination through structural coupling along the ontogeny of the organism of the relations of neuronal activity that the nervous system generates or maintains, invariant, is the phenomenon of learning. In general, then, due to the homeostatic nature of the autopoietic organization that ensures that this organization is actively maintained constant, while the structure of the organism changes, ontogenic adaptation, and learning if there is a nervous system, are necessary consequences of ontogeny: if ontogenic structural coupling of organism, nervous system and medium do not take place, the autopoietic system disintegrates. The same argument applies to the history of structural change of reproductively generated autopoietic activities. Such a history is organic evolution.

DESCRIPTIVE FALLACY

The process of structural coupling between two or more state-determined systems, one of which, at least, is autopoietic, as a historical process leading to the spatio-temporal coincidence between the changes of state of the coupled systems, arises as a necessary spontaneous consequence of the mutual operative restrictions to which the state-determined systems submit to each other during their interactions without loss of identity. This spatio-temporal coincidence in the changes of state of the coupled systems, however, is usually described by the observers as a semantic coupling, that is, as if it were the result of the computation by the autopoietic system (the organism) of its own adequate changes of state after gathering the proper information from the environment; in other words, as if the changes of state of the autopoietic system were determined by the environment. Such a description, though, does not reflect any phenomenon actually taking place among state determined systems: (a) because the notion of information is valid only in the descriptive domain as an expression of the cognitive uncertainty of

the observer, and does not represent any component actually operant in any mechanistic phenomenon in the physical space; and (b), because the changes of state of a state determined system, be it autopoietic or not, are determined by its structure, regardless of whether these changes of state are adequate or not for some purpose that the observer may consider applicable. Therefore, any description which implies a semantic coupling between structurally coupled state-determined systems, and which is not intended as a mere metaphor, is intrinsically inadequate and fallacious.

Implications

The fact that, as the previous characterizations show, an autopoietic system in the physical space, and the nervous system that may be one of its component subsystems, are closed systems, determines the occurrence of three distinct phenomenological domains that can be described as follows:

- (a) the domain of the internal changes of state of a system in which all state transitions occur without the system losing its identity;
- (b) the domain of perturbations of a system in which the system can interact through its components in the space in which it exists as a unity and, as a result, undergoes changes of structure without loss of identity; and,
- (c) the domain of interactions of a system as a (non-composite) unity in the space which its properties as a unity define, regardless of how these properties arise.

The first phenomenological domain is the domain of realization of a system as a system; in the case of an autopoietic system this domain is the domain of its autopoiesis to which everything in it is subordinated as a necessary condition for its existence; in the case of the nervous system this domain is the domain of its operation as a closed neuronal network. The second phenomenological domain is the domain of structural coupling of the organism and the nervous system to each other and to the medium in which the autopoiesis of the organism is realized, and, therefore, the domain in which the structural phenomena that we describe as adaptation and learning occur. The third phenomenological domain is the domain where cognition takes place as a phenomenon of observable manipulations of an environment, and where the observer arises as a system that can make descriptions, and always remain external to its circumstances by treating descriptions as objects of further descriptions.

The following are some general implications of this.

- (a) If the autopoiesis of an autopoietic unity is realized through a distributed structure that ensures a distributed autopoiesis, a simple mechanical fragmentation of the autopoietic unity (self-division or self-reproduction) produces at least two new autopoietic unities that may have identical or different structures according to how uniform was the component's distribution in the original unity. Heredity of organiza-

tion and structure with the possibility of hereditary structural change is, therefore, a necessary consequence of distributed autopoiesis. If there is differential realization of autopoiesis among structurally different autopoietic unities due to disuniformities in the medium in which they exist, evolution is a necessary consequence if the autopoietic unities are generated through self-division.

(b) All the states that an autopoietic system can adopt are states in autopoiesis, and are necessarily determined by its organization and structure, not by the perturbations arising in the medium in which it exists. Cognition, at whatever level of concreteness or abstraction, as a phenomenon of operation of the organism (as a unity) in its medium, also necessarily consists at the level of the internal dynamics of the unity in the actual realization of its autopoiesis. Therefore, in a strict sense, for any organism its cognitive domain is its actual domain of autopoiesis.

(c) If two plastic autopoietic systems interact, and their structures become ontogenetically coupled as a result of these interactions, a consensual domain of conduct is developed between the two organisms as a domain of conduct in which the participation that the conduct of one organism has for the realization of the autopoiesis of the other organism becomes determined during the interactions through their structural coupling. Such a consensual domain of conduct is a linguistic domain, and as such it is a domain of descriptions in which the conduct of one organism can be taken by an observer as a description of the consensual conduct which it elicits in the other organism.

(d) If an organism is capable of consensual conduct and of recursively interacting with its own states (through internal interactions of its closed nervous system), and applies the descriptive operation to itself by developing a consensual domain with itself through interactions with its own consensual states, a new phenomenological domain is generated that is indistinguishable from that which we call our domain of self-consciousness.

Comments

THE OBSERVER

Everything said is said by an observer to another observer; furthermore, the observer can always recursively be an observer of his observation and stay external to the description of his circumstances. This he can do because everything he does is mapped in the same domain: the domain of relative neuronal activity in his closed nervous system. Interactions of the nervous system with its own states of neuronal activity allow, in principle, for infinite recursion with continuous behavioural change. The domain of descriptions in which the observer arises when in the course of evolution the nervous system becomes able to recursively interact with its own states, is also a closed domain.

THE THEORY

The purpose of this theory is to give the fundamental set of necessary and sufficient notions capable of explaining all the phenomenology of living systems. Therefore, no attempt has been made to explain any particular biological phenomenon; all particular phenomena should be explainable by the theory if the proper contingent circumstances of their realization are taken into consideration. Also, I have made no attempt to give this theory a mathematical formalism, first, because I am incompetent to do it, and second, because I consider that such formalism is necessarily secondary to the complete conceptual statement of the theory which I have here presented.

Basic requirements that the theory satisfies are as follows.

(a) To use only simple operative concepts of immediate validity to any observer as a natural and as a scientific person.

(b) To state only necessary conditions that cannot be taken for granted. Thus, when talking of processes of production of components (such as molecules, polymers, etc.) no statement is made about their physical or chemical legality, obviously because in nature there only occur those chemical reactions or physical processes that can occur. Therefore, if a given set of components cannot generate the processes that constitute an autopoietic system, they do not constitute an autopoietic system, without this invalidating the notion of autopoiesis. A truism is implicit: autopoiesis takes place whenever it can take place.

(c) To specify only the conditions which generate phenomena that are isomorphic with the phenomena to be explained, and not with the description of the phenomena as they appear to the observer.

(d) To provide a mechanistic explanation for all biological phenomena, that is, to show that all biological phenomena arise from the interactions of the proper components, and not as an expression of the properties of some components.

(e) To point to conditions that can be realized through neighborhood relations without invoking organizing principles of any kind which pretend to subordinate the components to the whole. The unity, the whole, is the result of the interactions of the components through the realization of the organization that defines it, and not an operant factor in the interaction of the components that generate it. For the purpose of communication, an observer that beholds simultaneously the unity and its components may describe the latter with reference to the former, but this is merely a descriptive metaphor and not a reflection of the constitution of the unity. A unity if composite, is fully specified by specifying its organization.

To the extent that these basic requirements have been fulfilled, the theory reveals living systems as having a fundamentally simple organization which can arise spontaneously, and inevitably, in any part of the universe when certain conditions are given. All the

structural complexity of present-day living systems is the result of their evolutionary and ontogenic histories, and, therefore, irrelevant to the description of their organization.

POINTING TO A UNITY

The basic operation that an observer performs (although this operation is not exclusive to observers) is the operation of distinction; that is, the pointing to a unity by performing an operation which defines its boundaries and separates it from a background. The observer, then, always specifies the unity that he observes through some explicit or implicit operation of distinction, and always implies by his observation an organization in it that is compatible with its implied or specified boundaries if it is a composite unity. This is a fundamental point for three reasons.

(a) Given an operation of distinction that separates a unity by specifying its boundaries, usually there are many organizations that could define a unity with such boundaries as partial boundaries, but which would strictly specify different unities. There is, therefore, a communicative ambiguity in pointing to a unity if no explicit reference is made to its organization or to its being indicated through a total distinction, and two observers may disagree because through unspecified boundaries they may imply different unities, even though they may perform identical overt operations of partial distinction under the belief that they refer to the same unity.

(b) Different operations of total distinction separate different kinds of unities because they define different kinds of boundaries and, therefore, imply different organizations.

(c) The organization and structure of a unity specify all the operations of distinction through which it can be separated from the background.

It follows that it is always the task of the observer to specify the organization of the unity that he observes, or to imply it unambiguously through a complete operation of distinction.

THE PHYSICAL SPACE

I have said that living systems are autopoietic systems that exist in the physical space. Strictly, however, I should say that the physical space is the space in which living systems exist, and that this determines its singularity. In fact, since autopoietic systems are closed homeostatic systems that maintain constant their organization, all their changes of state are changes of state in autopoiesis and they can only be perturbed through the interactions of their components. Therefore the domain of perturbations of an autopoietic system is defined by the domain of interactions of its components, and exists as a domain of perturbations only in the domain in which these components exist. This

necessarily applies to us too, and, unless we explicitly suppose something different, this also applies to our cognitive processes. It follows that if cognitive processes are operations in autopoiesis, the space of our components is a limiting space outside of which we cannot step through cognition.

The physical space defined as the space in which living systems exist, then, is both ontologically and epistemologically singular; it is ontologically singular because it is constitutive to the phenomenology of living systems, and it is epistemologically singular because it defines the operational boundaries of our cognitive domain.

STRUCTURAL COUPLING

Two plastic systems become structurally coupled as a result of their sequential interactions when their respective structures undergo sequential changes without loss of identity. Therefore, the structural coupling of two independent structurally plastic unities is a necessary consequence of their interactions, and is greater the more interactions take place. If one of the plastic systems is an organism and the other its medium, the result is ontogenic adaptation of the organism to its medium. If the two plastic systems are organisms, the result of the ontogenic structural coupling is a consensual domain, that is, a domain of behaviour in which the structurally determined changes of state of the coupled organisms correspond to each other in interlocked sequences.

To an observer, the states of adaptation between organisms and environment, or between organisms in a consensual domain, appear as states of correspondance between plastic systems that can be described in terms of functional relations, that is as semantic couplings. The statements go like this: the function of such and such a structure in the organism is to cause such and such a change in the environment; or the meaning of the state of system A for system B is what determines the state to which system B passes as a result of the interaction of the two systems. Such a description in terms of functional relations is a description in terms of a semantic coupling because the structural correspondance between the interacting systems is considered without reference to its origin, and the changes of state of the coupled systems are treated as if they were determined externally by the perturbations, and not internally by the respective present structures of the interacting systems. If the fact that the mutual perturbations constitute only the historical instances under which the structurally coupled system undergo internally determined changes of state is neglected, four fundamental phenomena are ignored.

(a) That the result of the structural coupling of two or more systems is the structural determination of an interlocked order in the respective changes of state of the systems that is realized in the form of ordered sequences of mutually triggering perturbations.

(b) That if it were not the case that perturbations only constitute triggering circumstances for internally determined changes of state, inadequate behaviour, that is behaviour that for an observer appears out of context, would never take place.

(c) That semantic interactions, that is, interactions in which the perturbing agent determines the new state attained by the perturbed system, so not take place in the phenomenological domains of state determined systems, but only occur in the domain of description.

(d) That the domain of descriptions arises as a metadomain from the establishment of consensual domains by structurally coupled plastic systems (Maturana, 1970). Although the structural coupling is a historical process, that is, each structural innovation arises as a modification of a pre-existing structure and constitutes the basis for the next one, the structurally coupled unities always correspond to each other in the present. The history of a system may reveal how its structure arose, but it does not reveal how it operates in the present: the operation of a system is always the result of its present structure, not of its history, however, significant or complex this operation may seem in a historical perspective.

The nervous system operates in the present as a closed neuronal network that maintains constant, under continuous external (changes in the medium) and internal (its own states of neuronal activity) perturbations, certain relations of neuronal activity (describable either as internal neuronal correlations or as sensory-effector correlations) that have been specified or become specified through its structural coupling with the organism. If one considers the complexity of the things that people are able to do, such as talking, abstract thinking or ethical or political decisions, such a description of the nervous system seems insufficient. This insufficiency, however, is only apparent because the ethical, sociological or philosophical complexity of these human operations lies in their historical significance, not in the nature of the operations themselves.

The historical significance and, hence, the contextual complexity of any behaviour, is put in the descriptions by the observer who defines the domain of relevance of the observed behaviour in his domain of description. Relevance, meaning, function, significance, then, are terms which refer to the observable domain of interactions of the autopoietic unity as a unity, and not to its internal autopoietic changes of state. Therefore, the actual complexity of the operation of the nervous system is, exclusively, the complexity of an homeostatic closed neuronal activity that may be continuously changing through the structural coupling of the system to the medium (which may recursively include the nervous system itself) in which it exists.

SELF-REPRODUCTION

If the organization of an autopoietic unity and the

structure which realizes it are uniformly distributed across the expanse of the unity through a uniform distribution of components, self-reproduction is a trivial consequence of a simple mechanical fragmentation of the autopoietic unity, and heredity a necessary consequence of the uniform distribution of the components. In modern cells there are molecular components that are usually not uniformly distributed across the cell due to its internal compartmentalization, and must become uniformly distributed (through the dynamics of mitosis) before cellular fragmentation takes place. However, once the uniform distribution of components is obtained, everything occurs as stated above. No copying takes place, and no notion of program, of coding or transmission of information is necessary in order to account for the phenomena of self-reproduction and heredity.

Since it is the autopoietic organization that determines the unity of a living system, and since it is its structure that determines its mode of realization, it is intrinsically inadequate to consider any particular component as responsible of the properties of the system, and, least of all, of its hereditary characteristics. Notions such as program, coding or transmission of information do not apply to the operation of state-determined systems. These notions are useful, though conceptually misleading, as metaphors in the domain of description in which a mapping is made of the observed phenomenon upon the domain of purposeful design of the observer. An autopoietic unity, as is universally the case with every state-determined system, undergoes only the changes of state determined by its structure. The viral DNA that is sometimes referred to as a genetic message, does not specify what the host cell will do; the changes of state that the cell undergoes are determined by the structure of the cell under viral perturbation, but not by the viral DNA.

DESCRIPTIONS

A consensual domain ontogenically established through the structural coupling between two or more organisms appears to an observer as an interlocked domain of distinctions, indications or descriptions, according to how he considers the behaviour of the observed organisms. If the observer considers every distinguishable behaviour as a representation of the environmental circumstances which trigger it, he considers the behaviour as a *description*, and the consensual domain in which this behaviour takes place as a domain of interlocked *descriptions* of actual environmental states. What we do as observers when we make a description is exactly that, we behave in an interlocked manner with other observers in a consensual domain ontogenically generated through our direct (mother-child relation) or indirect (membership in the same society) structural coupling. Yet, if the observer forgets that the interlocked adequacy of the mutually triggering changes of state of the mutually perturbing systems in

the consensual domain is the result of their ontogenic structural coupling, he may *describe* the consensual domain as if it constituted an intrinsic descriptive system in which the descriptive interactions gave information to the organisms to compute the *ad hoc* states needed to handle the described environment.

The establishment of a domain of *descriptions* is not exclusive of autopoietic systems. Any collection of systems that can undergo ontogenic structural coupling can establish a consensual domain as a closed domain of interlocked interactions and, therefore, can participate in a domain of *descriptions* in which every *description* is a *description* only within the consensual domain. Furthermore, if a system that can make *descriptions* can be perturbed by its own states within the domain of *descriptions*, and thus generate *descriptions* of a medium that includes its *descriptions*, a second-order consensual domain is produced through the recursive application of *descriptions* on *descriptions*, and an observer is operationally generated. For this to take place, however, it is necessary that all perturbing agents, including the *descriptions*, should belong to the same class, so that the operation of *description* could be recursively applied to the product of its application. This is possible in organisms with a nervous system because the nervous system is a close neuronal network in which all states of activity are states of relative neuronal activity that only lead to other states of relative neuronal activity, independently of the circumstances of interactions of the organism in which these states of activity arise, a condition which necessarily results in the nervous system becoming recursively structurally coupled to its own structural changes. Since internally and externally generated states of relative neuronal activity in the nervous system are indistinguishable for the dynamics of states of the nervous system, the interactions of the nervous system with its own states that its closed organization implies, become, in the domain of interactions of the organism, descriptions of descriptions.

LINGUISTIC DOMAIN

A linguistic domain is a domain of consensual behaviour, ontogenically established between at least two structurally plastic organisms, that is usually described as a domain of semantic interactions. Yet, the semantic value of an interaction, in whatever domain, is not a property of the interaction, but a feature of the description that the observer makes by referring to it as if the changes of state of the interacting systems were determined by their mutual perturbations, and not by their respective individual structures. Therefore, the problem of establishing a linguistic domain is not the problem of establishing an operational semantic coupling, but the problem of establishing an operational semantic coupling, but the problem of establishing an ontogenic structural coupling that generates a consensual domain in which the coupled plastic systems can

undergo an unending series of interlocked alternating changes of state. In other words, linguistic behaviour is structurally determined behaviour in ontogenically structurally coupled organisms, in which the structural coupling determines the sequential order of the mutually triggering alternating changes of state. Semantics exists only in a metadomain of descriptions as a property projected upon the interacting systems by the observer, and valid only for him.

Descriptions as linguistic behaviour are no exception to this. The semantic value of a description exists only in a recursively-generated metadomain of descriptions of descriptions, not in the domain of operation in which a description is realized as an actual behaviour. The same happens with self-consciousness as a subdomain of self-descriptions in a domain of descriptions of descriptions (Maturana, 1970). In these circumstances, the changes of state of the nervous system that lead to self-description would not be different from other changes of state that lead to other descriptions, but would differ only in the consensual domain in which the descriptions arose and are applied.

It is the recursive application of descriptions in a domain of self-descriptions as the expression of a recursive structural coupling of the nervous system with its own structure in the sequential changes of state of a single system, that gives to self-consciousness its uncanny quality of a process which transforms a single system into two: the changes of state of a single system appear to an observer as if they were taking place through interactions with another. Otherwise, as occurs with any other behaviour, the determination of self-consciousness is structural and not semantic.

Conclusions

Although the fundamental conclusions are already contained in the previous sections, it may be worthwhile to summarize them in the following form.

(a) The constitutive feature of a living system is autopoiesis in the physical space; the constitutive feature of the nervous system is its condition of being a closed neuronal network.

(b) All changes of state in the living system and in its nervous system are subordinated to the realization of the autopoiesis of the living system, if this does not occur the autopoiesis stops and the living system disintegrates.

(c) If the organism and its nervous system are structurally plastic, the continuous realization of the autopoiesis of the organism necessarily results in a structural coupling of the organism and nervous system to each other, and to the medium in which the autopoiesis is realized.

(d) The result of this structural coupling is that although the organism operates only in autopoiesis, and the nervous system operates only in generating internal relations of neuronal activity, each determined by its

own structure, the changes of state of the organism and the nervous system, and the changes of state of the medium, mutually trigger each other in a manner that leads to continued autopoiesis. As a result, if an organism were to be taken out of the medium to which it is structurally coupled, it would go on in its structurally determined changes of state regardless of their inadequacy to the changes of state of the new medium, and, eventually, disintegrate.

(e) Descriptions in terms of information transfer, coding and computations of adequate states, are fallacious because they only reflect the observer's domain of purposeful design and not the dynamics of the system as a state-determined system.

(f) The observable complexities of the domain of interactions of an autopoietic unity as a unity, are complexities proper to the historical circumstances in which the changes of state of the unity take place, not to the processes that constitute the internal changes of state of the unity itself, the nervous system included. The organization and structure of an autopoietic unity do not include operational elements proper to the domain in which it interacts as a unity.

(g) Any recursive operation in an organism, or in its nervous system, is the application of the same opera-

tion on different states of a structurally changing system with invariant organization, that can take place only because the results of the application of the repeated operation is applied. This is what obviously takes place in the nervous system which, as a closed neuronal network, only adopts states of relative neuronal activity that lead to new states of relative neuronal activity. Such a recursion in the descriptive domain is necessary to generate self-consciousness as a new phenomenological domain.

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Self-Organization of Living Systems: A Formal Model of Autopoiesis

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(Received August 9, 1976; In final form November 15, 1976)

A formalization, computerization and extension of the original Varela-Maturana-Urbe model of *autopoiesis* is presented. Autopoietic systems are driven by sets of simple "rules" which guide the behavior of components in a given milieu. These rules are capable of producing systemic structures that are far more complex than we could ever achieve by a direct arrangement of components, i.e., by a method of systems analysis and design. The study of autopoietic systems indicates that the traditional emphasis on internal qualities of system's components has been misplaced. It is the *organization* of components, rather than components themselves (or their structural manifestations), that provides the necessary and sufficient conditions of autopoiesis and thus of life itself. The dynamic autonomy of autopoietic systems contrasts significantly with the non-autonomous, *allopoietic* mechanistic systems.

INDEX TERMS Autopoiesis, allopoiesis, autogenesis, biological clock, social autopoiesis, human systems management, production, disintegration, bonding, catalytic neighborhood, APL-autopoiesis.

1 Introduction

In 1974 three Chilean scientists, F. G. Varela, H. R. Maturana and R. B. Uribe, published a seminal article,¹ entitled "Autopoiesis: The Organization of Living Systems, Its Characterization and A Model," providing a new direction as well as a new hope in contemporary theory of living systems. Their work could represent the first significant advance toward the general theory of organizations since the advents of Trentowski's *Cybernetyka*,² Bogdanov's *Tectology*,³ Leduc's *Synthetic Biology*,⁴ Smuts' *Holism*⁵ and von Hayek's *Spontaneous Social Orders*.⁶

In this article we deal with *organic systems*, i.e., both biological and social organizations displaying the fuzzily defined quality called "life." They are characterized by their self-renewal, self-maintenance and stability in a given environmental domain. The process of a continuous self-renewal of a systemic whole is called autopoiesis, i.e., self-production.

Autopoietic organization is realized as an autonomous and self-maintaining unity through an independent network of component-producing processes such that the components, through their interaction, generate recursively *the same* network of processes which produced them.

The product of an autopoietic organization is thus not different from the organization itself. A cell produces

cell-forming molecules, an organism keeps renewing its defining organs, a social group "produces" group-maintaining individuals, etc. Such autopoietic systems are organizationally *closed* and structurally state-determined,^{7,8} with no apparent inputs and outputs.

In contrast, the product of an *allopoietic organization* is different from the organization itself, it does not produce the components and processes which would realize it as a distinct unity. Thus, allopoietic systems are not perceived as "living" and are usually referred to as mechanistic or contrived systems. Their organization is *open*, i.e., with apparent inputs and outputs. For example, spatially determined structures, like crystals or macromolecular chains, machines, formal hierarchies, etc., are allopoietic.

It is important to distinguish between *organization* and *structure* of an organic system in this context. We shall paraphrase the original thoughts advanced by Maturana and Varela.^{9,10}

A given system, observed as a distinct unity in its environment domain, can be viewed as a whole of interrelated and further unspecified components.

A network of interactions between the components, renewing the system as a distinct unity, constitutes the *organization* of the system. The actual spatial arrangement of components and their relations, integrating the system temporarily in a given physical milieu, constitutes its *structure*.

The unity and holism of systemic organization *and* structure represents what is commonly referred to as a *system*.

Thus, two distinct systems may have the same organization but different structures. Structural changes do not reflect changes in the system as a unity

The article first appeared in *International Journal of General Systems*, Vol. 4, No. 1, 1977 published by Gordon and Breach Science Publishers, Ltd. We appreciate the permission of the publisher to re-typeset the article.

as long as its organization remains invariant. A system and its organization cannot be explained by simply reproducing its structure. The structure of a system determines the way its components interact between themselves, with their environment and with the observer.

Organizationally closed systems are not structurally separated from their environment; they are interacting and coupled with it. Although they do not have inputs or outputs, they can be externally perturbed and undergo structural adaptations. Any autopoietic system can be perceived as being allopoietic by specifying its input/output surfaces, i.e., by disconnecting its organizational closure, either experimentally or mentally.

Allopoietic systems are organizationally open, they produce something different than themselves. Their boundaries are observer-dependent, their input and output surfaces connect them mechanically with their environment. Their *purpose*, as an interpretation of their input/output relation, lies solely in the domain of the observer.

Further discussions along the above lines can be found in a variety of related works.¹¹⁻¹⁴

2 Autopoietic Model Of A Cell

One of the simplest autopoietic systems exhibiting the minimum organization of components necessary for autopoiesis, is a model of a biological cell. There is a catalytic nucleus capable of interaction with the medium of substrate so that the membrane-forming components can be continually produced. The resulting structure displays a membranous boundary that defines the system as a separate and autonomous unity in the space of its components.

In accordance with this basic organization of a cell, the simplest model of its autopoiesis must consist of a medium of substrate, a catalyst capable of producing more complex components-links, which are in turn capable of bonding, ultimately concatenating into a membrane surrounding the catalyst.

We shall designate the basic components of the model by the following symbols:

hole (H)	(space)
substrate (S)	○
free link (L)	□
singly bonded link (B)	□ —
fully bonded link (B)	— □ —
catalyst (C)	★

The original Varela-Maturana-Urbe model¹ was based on the following organization of components:

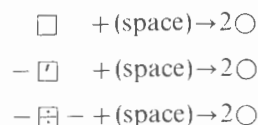
2.1 Production



A catalyst and two units of substrate produce a

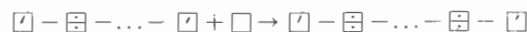
free link and a hole, while the catalyst is assumed to be essentially unaffected by this operation. Production can take place when a pair of substrate is in the predetermined neighborhood of the catalyst. Catalytic "reach" or the strength of ★ and its dynamics can be effectively simulated.

2.2 Disintegration



Any link, free or bonded, can disintegrate into two units of substrate. Additional unit of substrate will occupy an available hole which must be in the neighborhood of a disintegrating component.

2.3 Bonding



A free link can bond with a chain of bonded links; two chains of bonded links can be bonded into one, or re-bonded after their connecting link has disintegrated; two free links can be bonded together to start a chain formation.

Observe that disintegration and bonding are operations that do not require catalyst; they are "self-catalytic." That does not mean that the catalyst has no influence over those operations. For example, bonding can take place only beyond a predetermined catalytic neighborhood while disintegration can appear anywhere in the space.

More detailed rules, guiding the movement of all components and specifying the necessary conditions for the three interactive rules above, are discussed in the next section. Spontaneous encounters, bonding and disintegration of components is partially guided by chance. We shall only briefly summarize some additional properties.^{1, 13, 15, 16}

Each component (and its corresponding neighborhood) is allowed to move over the space according to predetermined rules. A set of dominance relations must be established in order to prevent different components claiming the same space during the same unit time-interval. Any component can claim a hole, a link can displace a substrate, and a catalyst can displace both substrates and links. Thus ★ > □ > ○ > (space) establishes this partial dominance. We do not allow any movement of bonded links.

Each link can have at most two bonds: it can be either free, □, single bonded, — □, or fully bonded,

— — —. Additional bonds, — — —, are of course

possible, but they induce frequent branching of chains, creating thus catalyst-free enclosures. Multiple bonds are indispensable for modeling in a three dimensional space.

Unbranched chains of bonded links will ultimately form a membrane around the catalyst, creating the enclosure impenetrable for both \star and \square . These two components are thus effectively "trapped" and forced to function for the benefit of the autopoietic unity. Substrate units, \bigcirc , can pass freely through the membrane and thus keep the catalyst supplied for the production of additional \square . Any disintegrated links, causing ruptures in the membrane, and thus be readily and effectively repaired by the ongoing production. The unity of the system is recursively maintained through a series of minor structural adaptations.

In Figure 1, we present a sample of APL printouts providing typical "snapshots" from the "history" of an autopoietic unity.

3 A Formal Model of Autopoiesis

3.1 Introductory Concepts

Let us define a two-dimensional (Cartesian) tessellation grid: A *space* of an autopoietic automaton. The *grid* G consists of a countably infinite set of *positions*, each position referred to by a unique pair of integers (i, j) , positive or negative. For practical purposes we shall consider that the underlying network of positions forms an n -dimensional Cartesian grid, i.e., it has the nature of an *Abelian group*.¹⁷

An Abelian-group cellular automaton Γ is an ordered quintuple:

$$\Gamma = (Q, M^0, +, f, H)$$

where

- (i) Q is a set of states
 - (ii) $M^0 = \{M_1, \dots, M_m\}$ is a generator set of a finite-generated Abelian group having group operation "+", i.e., vector addition.
 - (iii) f is the local transition function, a *set of rules*, a mapping from $Q(t)$ to $Q(t+1)$.
 - (iv) H is the quiescent state, such that $f(H, \dots, H) = H$.
- The *neighborhood* of any position k in G is defined as the set

$$N(k) = \{k, k + M_1, k + M_2, \dots, k + M_m\}.$$

The meaning of f , then, is that an assignment of states to $N(k)$ helps to determine the next state of k .

A *form* F is an assignment of states to all positions of an automaton. A *finite form* is one in which all but a

finite number of positions are assigned the quiescent state H . The operation of Γ is assumed to proceed in unit time-intervals, $t_0, t_1 = t_0 + 1, t_2 = t_1 + 1, \dots$, the local transition function being applied *simultaneously* to all positions of G during each time-interval, thus generating a sequence of forms F_0, F_1, F_2, \dots

Example. Conway's "Life" cellular automaton, recently popularized by Gardner,³⁶ can be described as follows: $Q = \{0, 1\}$, $H = 0$, and G is the Abelian group generated by

$$M^0 = \{(1, 0), (0, 1), (1, 1), (-1, 0), (0, -1), (-1, -1), (1, -1), (-1, 1)\}$$

under the operation of vector addition. Each position has exactly eight neighboring positions, the *Moore neighborhood* $N(k)$ for a given k , determined by M^0 . Let f be defined as follows:

- 1) If at time t the state of k is 0 and there are *exactly* three positions in state 1 in $N(k)$, then at time $t + 1$ the state of k will become 1.
- 2) If at time t the state of k is 1 and there are exactly two or three positions in state 1 in $N(k)$, then at time $t + 1$ the state of k will remain 1.
- 3) If at time t position k and its $N(k)$ do not satisfy either condition 1 or 2, then at time $t + 1$ position k will be in state 0.

These three conditions adequately define f and enable us, given any configuration at time t , effectively determine the configuration at time $t + 1$.

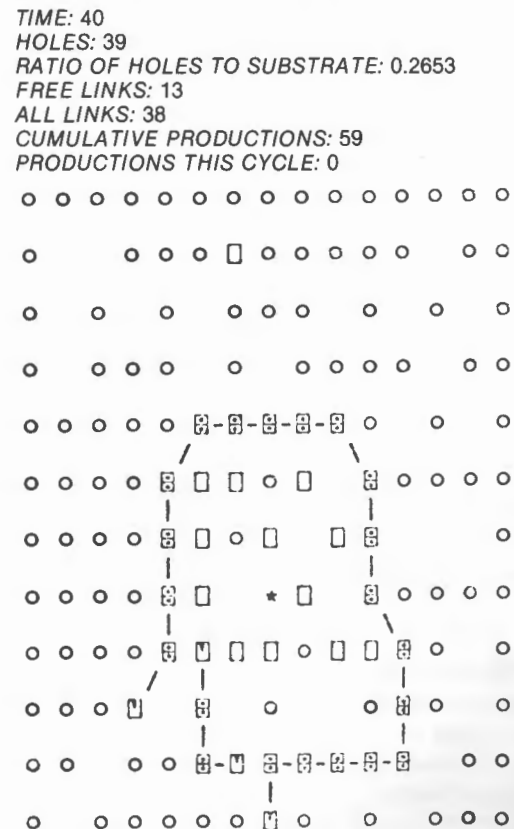
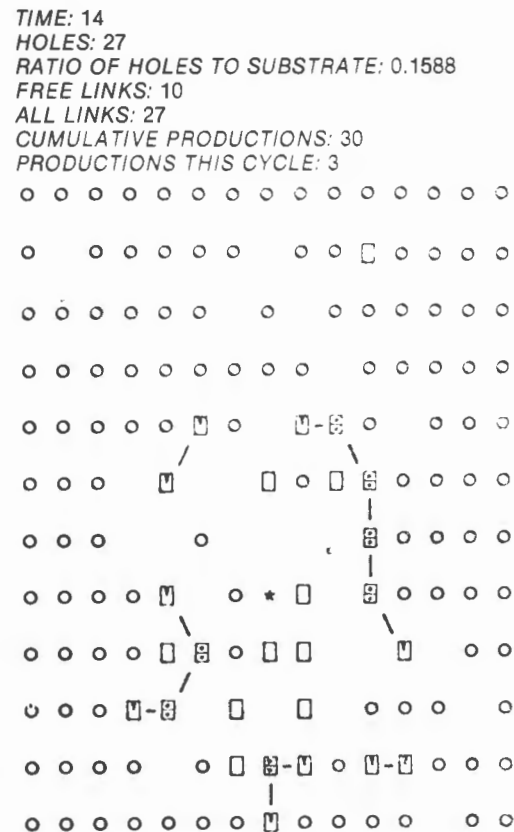
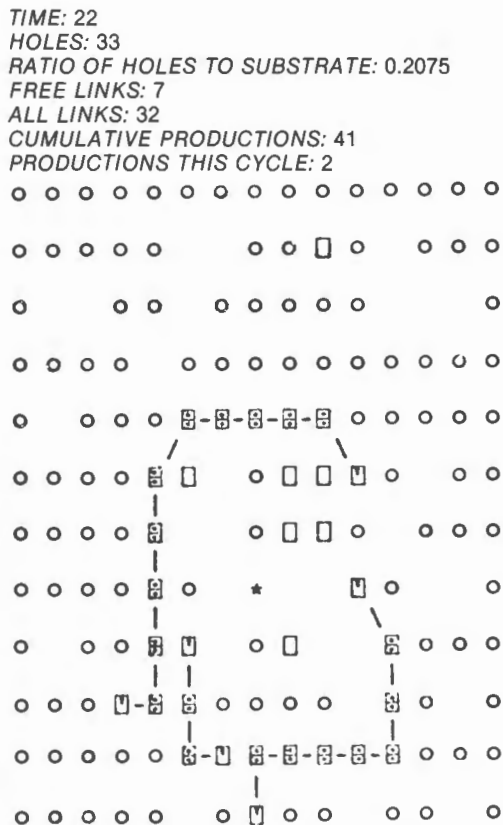
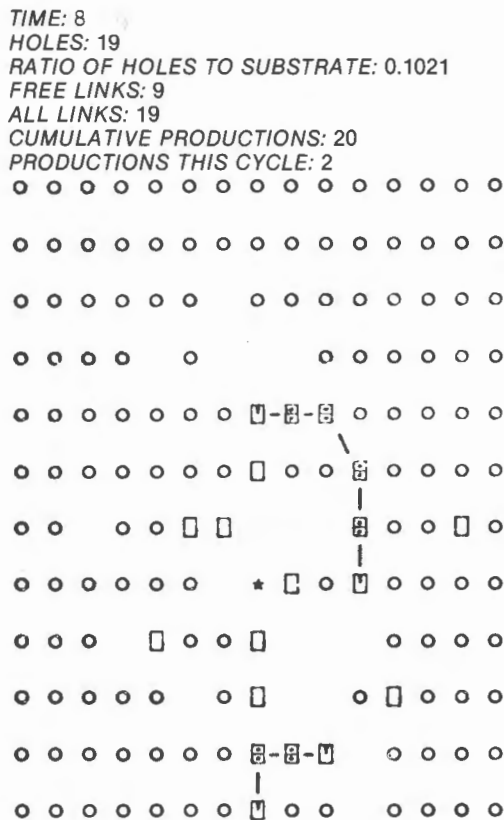


FIGURE 1 Structural history of an autopoietic unity. Observe the gradual build up of organized "matter" until dynamic equilibrium is reached and maintained.

3.2 A Model of Autopoiesis

We shall allow the neighborhood of a position to "wander" throughout a constant Abelian space. That is, a state is distinct from a position of the space and is identified with a shifting set of "interdependent positions" in the space.

Each position is identifiable as (i,j) , $i,j = 1, \dots, n$. We define a complete general neighborhood of $k \equiv (i,j), N(k)$, as follows:

$$N(k) = \{k + \lambda_r M_r \mid r = 1, \dots, 8\},$$

where M_r indicates one of the eight possible directions over a Cartesian grid and λ_r represents the number of steps taken. Thus, the Moore neighborhood is characterized by all $\lambda_r = 1$, the von Neumann neighborhood has $\lambda_r = 0$ for all "diagonal" directions and $\lambda_r = 1$ for the rectangular ones, etc. By varying λ_r 's from 0 to n we can generate a large variety of neighborhoods, depending on a given context.

We shall turn our attention to a very simple and specific neighborhood, depicted in Figure 2. We assume that any movement can proceed in a rectangular fashion only and the complete neighborhood consists of all positions reachable through either one or two moves, i.e., $\lambda_r = 1$ or 2 for all rectangular movements. Thus,

$$M^0 = \{M_r \mid M_1 = (-1,0), M_2 = (0,1), \\ M_3 = (1,0), M_4 = (0,-1)\}.$$

In Figure 2 observe that M_1 through M_4 correspond to four basic directions: North, East, South and West. To establish a circular relation between operators M_r , we shall define

$$M_{4+i} = M_i.$$

We can demonstrate the usage of basic movement operators as follows:

$$\begin{aligned} (i,j) + M_1 &= (i-1,j) \\ (i-1,j) + M_3 &= (i,j) \\ (i,j) + 2M_1 &= (i-2,j) \\ (i,j) + M_2 + M_3 &= (i+1,j+1), \text{ etc.} \end{aligned}$$

The set of all possible states, Q , is defined as follows: $Q = \{H, S, L, B, C\}$, where

$$\begin{aligned} H(i,j) &\equiv H(k): \text{hole (a quiescent state)} \\ S(i,j) &\equiv S(k): \text{substrate} \\ L(i,j) &\equiv L(k): \text{(free) link} \\ B(i,j) &\equiv B(k): \text{bonded link} \\ C(i,j) &\equiv C(k): \text{catalyst} \end{aligned}$$

In general, $k \equiv (i,j)$ and $E(k) \equiv E(i,j)$ denotes a position k being in state E , i.e., any element of Q .

In Figure 2 observe that $n \leq 3$, $i, j \leq 2$, $i, j \geq n-1$, only incomplete neighborhoods can be defined. We shall

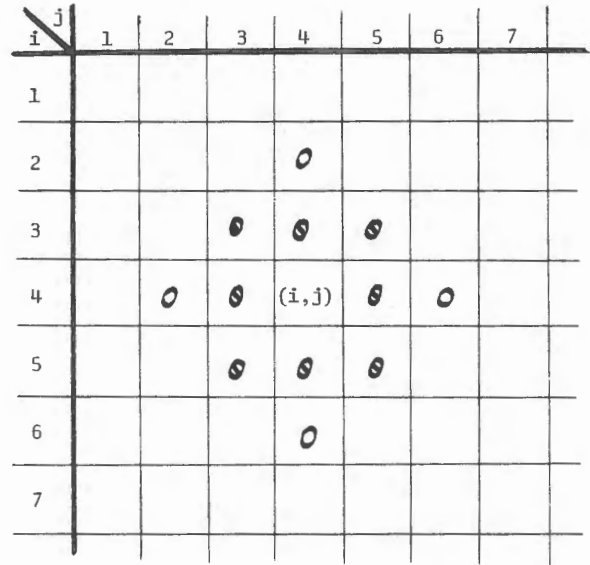


FIGURE 2 Complete neighborhood of any position (i,j) reachable by one or two rectangular moves. The Moore neighborhood is indicated by the eight marked elements.

state simple boundary conditions:

$$\begin{aligned} E(i,2) + M_1 &= E(i,2) \\ E(2,j) + M_2 &= E(2,j) \\ E(i,n-1) + M_3 &= E(i,n-1) \\ E(n-1,j) + M_4 &= E(n-1,j). \end{aligned}$$

Since all movements over $N(k)$ are carried with respect to k , we can further simplify our notation by not repeating k every time. Thus, we use E instead of $E(k)$, $E(M_r)$ instead of $E(k + M_r)$, etc. For example, for $k \equiv (i,j)$ and $M_r \equiv M_1$, instead of $E(k + M_1 + M_1)$ we use $E(2M_1)$ to designate that position $(i-2,j)$ is in state E .

There are two essential ways of moving over $N(k)$:

- select a direction M_r and a number of steps λ_r , and then identify the state of $(k + \lambda_r M_r)$.
- select a state E and then identify all positions of $N(k)$ being in that state as well as the directions to reach them from k .

With respect to (ii), for example, M_E indicates that $(k + M_E)$ position, $M_E \in M^0$, is in state E . In other words

$$E(M_E) \equiv H(k + M_E) \equiv H(M_E).$$

Let

$$D_E = \{M_E \in M^0 \mid E(k + M_E)\}.$$

designate a subset of M^0 such that $k + M_E$ position is in state E .

Often we use a series of operators to identify a given position: it is always the last operator which identifies the state. For example,

E means that k is in state E

$E(M_r)$ means that $(k + M_r)$ is in any state E because $M_r \in M^0$
 $E(M_r + M_E)$ means that $(k + M_r + M_E)$ is in a particular state E because $M_E \in D_E$.

Note. M_E identifies a position only in a complete $N(k)$. I.e., only two operators in succession are subject to the above interpretations. We can however use any number of operators to explore the situation beyond a given $N(k)$. For example, $E(M_r + 2M_E)$ means that $(k + M_r + M_E)$ is in a particular state E but we are identifying the position adjacent in direction M_E , i.e. $(k + M_r + M_E + M_E)$ which could be in any state E . It is therefore possible to write, for example, $H(M_r + 2M_B)$ but not $H(M_r + M_B)$; that could only be written as either $H(M_r + M_t)$, or $H(M_B + M_r)$, or $B(M_r + M_B)$. Similarly, $E(M_r + M_t + 2M_E)$ means that position $(k + M_r + M_t + 2M_E)$ is in state E but M_E direction has been determined independently. That is, there is some $E(M_r + M_E)$ and we use the corresponding direction M_E for exploring beyond the $N(k)$ after both M_r and M_t have been selected. We can write, for example, $H(M_r + M_t + 2M_B)$ or even $B(M_r + M_t + 2M_B)$.

Because we deal with an evolutionary system, we would like to make use of a "blind generation procedure," at least partially. It is necessary to preserve some randomness because a real-world environment has no known, complete, finite description or prediction. Let R_r indicate an element M_r randomly selected from M^0 and let R_E indicate an element M_E of D_E , also chosen at random.

Now we are ready to define our transition function f , a set of rules similar to those of Conway's "game of life." We shall use an arrow, \rightarrow , to denote a transition operator, i.e., $a \rightarrow b$ means "a is to be replaced by b." Similarly, $a, b \rightarrow c, d$ would read "a is to be replaced by c and b is to be replaced by d," etc.

3.2.1 Motion 1

Let $\mathcal{H} = \{H(k) \mid \text{coordinate set of all holes}\}$ and for each hole let R_r be randomly chosen from M^0 . Units of substrate, links and catalysts can move into their adjacent holes. Substrate can even pass through a bonded link segment while neither free link nor catalyst can do so. Both bonded links and holes are subject to no motion at all.

$$\begin{aligned} H, H(R_r) &\rightarrow H, H(M_r) \\ H, S(R_r) &\rightarrow S, H(M_r) \\ H, L(R_r) &\rightarrow L, H(M_r) \\ H, B(R_r), S(2M_r) &\rightarrow S, B(M_r), H(2M_r) \\ H, C(R_r) &\rightarrow C, H(M_r) \end{aligned}$$

After *Motion 1* any moved links are bonded, if possible, according to the rules of *Bonding*.

3.2.2 Motion 2

Let $\mathcal{L} = \{L(k) \mid \text{coordinate set of all free links}\}$ and for each link choose R_r at random from M^0 . If position $(k + R_r)$ contains another link, bonded link or catalyst, then no movement of free links ensues. That is,

$$\begin{aligned} L, L(R_r) &\rightarrow L, L(M_r) \\ L, B(R_r) &\rightarrow L, B(M_r) \\ L, C(R_r) &\rightarrow L, C(M_r) \end{aligned}$$

On the other hand, a free link can displace units of substrate into adjacent holes or exchange positions with them. It can also push a substrate into a hole through a bonded link. If the adjacent position is a hole then the link simply moves in. Assume that R_H and R_B have been randomly selected from D_H and D_B respectively. If position $(k + R_r)$ contains a substrate, we write as follows:

$$\begin{aligned} L, S(R_r), H(M_r + R_H) &\rightarrow H, L(M_r), S(M_r + M_H) \\ L, S(R_r), B(M_r + R_B), H(M_r + 2M_B) &\rightarrow \\ &H, L(M_r), B(M_r + M_B), S(M_r + 2M_B) \\ L, S(R_r) &\rightarrow S, L(M_r) \\ L, H(R_r) &\rightarrow H, L(M_r) \end{aligned}$$

Again, we bond any displaced links, if possible, according to the rules of *Bonding*.

3.2.3 Motion 3

Let $\mathcal{C} = \{C(k) \mid \text{coordinate set of all catalysts}\}$ and for each catalyst choose R_r at random from M^0 . There is no movement if the adjacent position contains either a bonded link or another catalyst. That is,

$$\begin{aligned} C, B(R_r) &\rightarrow C, B(M_r) \\ C, C(R_r) &\rightarrow C, C(M_r) \end{aligned}$$

If the adjacent position contains a free link, displaceable according to *Motion 2*, then the catalyst will displace it:

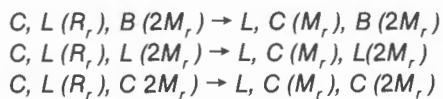
$$\begin{aligned} C, L(R_r), S(2M_r), H(2M_r + R_H) &\rightarrow \\ &H, C(M_r), L(2M_r), S(2M_r + M_H) \\ C, L(R_r), S(2M_r), B(2M_r + R_B), H(2M_r + 2M_B) &\rightarrow \\ &H, C(M_r), L(2M_r), B(2M_r + M_B), S(2M_r + 2M_B) \\ C, L(R_r), H(2M_r) &\rightarrow H, C(M_r), L(2M_r) \end{aligned}$$

If the adjacent position contains a substrate, displaceable according to *Motion 2*, then it will be moved as follows:

$$\begin{aligned} C, S(R_r), H(M_r + R_H) &\rightarrow H, C(M_r), S(M_r + M_H) \\ C, S(R_r), B(M_r + R_B), M_r + R_B, H(M_r + 2M_B) &\rightarrow \\ &H, C(M_r), B(M_r + M_B), S(M_r + 2M_B) \\ C, S(R_r) &\rightarrow S, C(M_r) \end{aligned}$$

If the adjacent position contains a free link which cannot be moved according to the rules of *Motion 2*, then

the catalyst will exchange its position with it:



and also



Then bond any displaced links, if possible, according to the rules of *Bonding*.

3.2.4 Production

Whenever two adjacent positions of a catalyst are occupied by substrate units, a link can be produced. Each such production leaves a new hole in the space. We allow *only one* link to form at each step, per each catalyst, although such rate of production can be varied. The choice of a link-producing pair of substrate is made at random.

Thus, for a given $C(k)$ we must list all adjacent positions containing a substrate the adjacent position of which is another substrate. We shall define

$$V_S = \{ M_S | S(M_S) \cup S(M_S + M_{S+1}) \}$$

as a set of *basic* movement operators from M^0 leading to a substrate in the Moore (i.e., rectangular) neighborhood of $C(k)$. Then for

$$E(M_S + M_{S+1}),$$

we define

$$X_S = \begin{cases} M_S + M_{S+1} & \text{if } E \equiv S \\ M_S & \text{always} \end{cases}$$

Thus, $X_S \in W_S = \{ X_S | S(X_S) \}$, where W_S is the set of all operators and their combinations leading to the positions containing substrate in the Moore neighborhood.

Let us form the Cartesian product of W_S with itself, i.e.,

$$W_S \times W_S = \{ \bar{X}_S | \bar{X}_S = (X_{S1}, X_{S2}) \},$$

i.e., the set of all pairs of operators X_S designated by \bar{X}_S . Then we define

$$P = \{ \bar{X}_S | X_{S1} - X_{S2} = M_r \}$$

as the set of pairs of operators leading to adjacent pairs of substrate. As an example, consider the situation in Figure 3, where

$$V_S = \{ M_1, M_2, M_3, M_4 \}$$

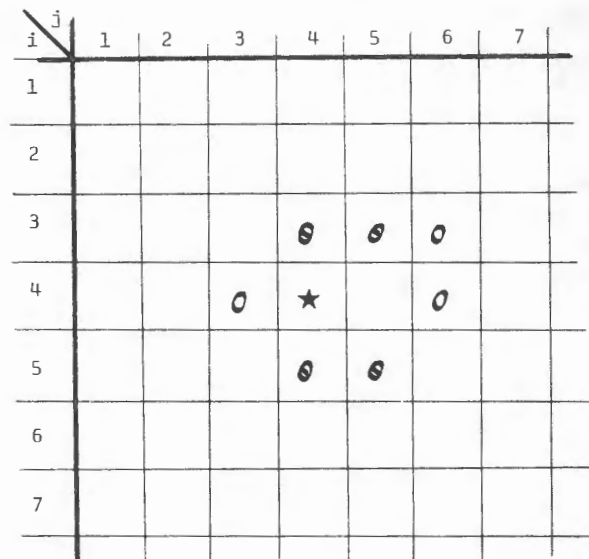


FIGURE 3 An example illustrating identification of the pairs of substrate (marked) available for production of links.

and

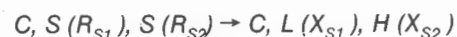
$$W_S = \{ M_1, M_1 + M_2, M_2 + M_3, M_3, M_4 \}.$$

We obtain

$$P = \{ (M_1, M_1 + M_2), (M_2 + M_3, M_3) \}$$

as the set of positions where a link can be produced.

Let $P \neq \emptyset$ for a given C . Let \bar{R}_S indicate a randomly selected pair from P . Obviously, $\bar{R}_S = (R_{S1}, R_{S2})$ and we can write the production rule as follows:



Note that one substrate is replaced by a free link while the other substrate is "removed." Recall that two substrates are used to produce a link. Try to bond any newly produced link according to the rules of *Bonding*.

3.2.5 Disintegration

Each free or bonded link, $L(k)$ or $B(k)$, can disintegrate into two units of substrate, providing there is a hole in the neighborhood into which the additional substrate could sink. To identify the suitable holes we shall define the following sets of movement operators:

$$T_1 = \left\{ M_{S1} | S(M_{S1}) \cap \left[\bigcup_{i=S1-1}^{S1+1} H(M_{S1} + M_i) \right] \right\}$$

and

$$T_2 = \left\{ M_{S2} | S(M_{S2}) \cap \right.$$

$$\cap \left[\bigcup_{i=S_2-1}^{S_2+1} B(M_{S_2} + M_i) \cap H(M_{S_2} + 2M_i) \right]$$

Observe that these two sets identify neighboring holes into which a substrate can be pushed either directly or through a bonded link, thus making a room for disintegration.

Let $N = \{n \mid n \in (0, 1)\}$ and R_N be a uniform random number selected from N . If, say, $R_N \leq K$, where K is predetermined and adjustable parameter, then the chosen link disintegrates. Again, the actual rate of disintegration can be controlled and harmonized with the rate of production. Let $E(k)$ represent either $L(k)$ or $B(k)$ and let us select, randomly, R_H , R_B , R_{T1} , and R_{T2} . Then the following set of rules guides *Disintegration*:

$$E, H(R_H) \rightarrow S, S(M_H)$$

$$E, S(R_{T1}), H(M_{T1} + R_H) \rightarrow S, S(M_{T1}), S(M_{T1} + M_H)$$

$$E, S(R_{T1}), B(M_{T2} + R_B), H(M_{T2} + 2M_B) \rightarrow S, S(M_{T2}), B(M_{T2} + M_B), S(M_{T2} + 2M_B)$$

As a next step we attempt to re-bond according to the rules of *Re-bonding*. Then proceed to explore the next $L(k)$ or $B(k)$.

3.2.6 Bonding

Every free link is a candidate to be bonded with another free link or with a singly bonded link. A bonded link, B , is always a component of a chain of bonded links. We shall designate a bonded link in the α th chain by $B^\alpha(k)$.

For a given $L(k)$ we locate all neighboring positions containing free links, namely $I_L = \{M_L \mid L(M_L)\}$. Similarly, we locate all singly bonded links in the neighborhood, say K_B :

$$K_B = \left\{ M_B \mid B^\alpha(M_B) \cap \left[\bigcup_{i=B-1}^{B+1} B^\alpha(M_B + M_i) \right] \right\}$$

Let us form a set of all possible pairs of eligible singly bonded links by forming the Cartesian product of K_B with itself:

$$K = K_B \times K_B = \{ \bar{M}_B \mid \bar{M}_B = (M_{B1}, M_{B2}) \}.$$

If $K \neq \emptyset$ we perform the following transformation for $\alpha \in \mathcal{B}$ and $\bar{R}_B = (R_{B1}, R_{B2})$:

$$L, B^\alpha(R_{B1}), B^\beta(R_{B2}) \rightarrow B^\alpha, B^\alpha(M_{B1}), B^\beta(M_{B2})$$

If $K = \emptyset$, but $K_B \neq \emptyset$, then there is exactly one singly bonded link and we can form the bond as follows:

$$L, B^\alpha(M_B) \rightarrow B^\alpha, B^\alpha(M_B)$$

Let us define K_L analogously with K_B . Then if $K_L = \emptyset$, exit. Otherwise, select one free link and form the bond as follows:

$$B^\alpha, L(R_L) \rightarrow B^\alpha, B^\alpha(M_L)$$

Test $K_L = \emptyset$ again; if Yes, exit. Otherwise, select one free link and form the corresponding bond:

$$L, L(R_L) \rightarrow B^\alpha, B^\alpha(M_L)$$

Next, perform the following operation (symbol \sim stands for logical negation):

$$I_L \rightarrow I_L \cap \sim \{M_L\} \text{ since } E(M_L), E \neq L.$$

If $I_L \neq \emptyset$, repeat the $K_L = \emptyset$ test and perform

$$\alpha, L(R_L) \rightarrow B^\alpha, B^\alpha(M_L)$$

again. Then exit.

3.2.7 Re-Bonding

In place of each disintegrated link, free or bonded, we attempt to re-bond a disconnected chain of bonded segments. To that purpose, for any position k , we have to determine all neighborhood positions occupied by singly bonded links. First,

$$V_B = \{ M_B \mid B(M_B) \cup B(M_B + M_{B+1}) \}.$$

Then, for $E(M_B + M_{B+1})$, we determine

$$X_B = \begin{cases} M_B + M_{B+1} & \text{if } E \equiv B \\ M_B & \text{always} \end{cases}$$

Thus $X_B \in Y_B$, where

$$Y_B = \{ X_B \mid B^\alpha(X_B) \cap \left[\bigcup_{i=B-1}^{B+1} B^\alpha(M_B + M_i) \right] \}$$

is the set of all "bondable" singly bonded links. We form a list of pairs of such links:

$$Y_B \times Y_B = \{ \bar{X}_B \mid \bar{X}_B = (X_{B1}, X_{B2}) \}$$

$$Z'_B = \{ \bar{X}_B \mid X_{B1} - X_{B2} = M_r \}$$

$$Z''_B = Z'_B \cap \sim \{ \bar{X}_B \mid B^\alpha(X_{B1}) \cap B^\beta(X_{B2}) \},$$

where Z''_B determines pairs of singly bonded links \bar{X}_B that can be bonded. Let us define the following set:

$$\{ X_e \mid \bar{X}_{B1} \cap \bar{X}_{B2} = X_{B=e} = X_e \},$$

where \bar{X}_{B_i} and \bar{X}_{B_j} are particular pairs of Z''_B . For each such X_e , form the set $e = \{\bar{X}_{B_i}, \bar{X}_{B_j}\}$. Let \bar{R}_e be a pair selected at random from e , i.e., $\bar{R}_e = \bar{X}_{B_i}$ or \bar{X}_{B_j} and

$$Z_B = Z''_B \cap \sim \left\{ \bigcup_e \bar{R}_e \right\}.$$

Then for each $\bar{X}_B \in Z_B$ we have the following rule of re-bonding:

$$B^\alpha(X_{B_1}), B^\beta(X_{B_2}) \rightarrow B^\alpha(X_{B_1}), B^\alpha(X_{B_2})$$

Define $Y_B \cap \sim \{X_B | X_B \in \bar{X}_B \in Z_B\}$. Then

$$Y_B \rightarrow [Y_B \cap \sim \{X_B\}] \cup \{X_L\}.$$

where X_L is derived as follows:

$$V_L = \{M_L | L(M_L) \cup L(M_L + M_{L+1})\}$$

and for $E(M_L + M_{L+1})$:

$$X_L = \begin{cases} M_L + M_{L+1} & \text{if } E \equiv L \\ M_L & \text{always.} \end{cases}$$

Next, use the new Y_B to construct new Z''_B and Z_B and apply the rule of re-bonding again. Then exit.

4 Experiments in Self-Organization

Our formalization of a parallel process is very flexible. Catalytic neighborhoods can change their sizes and shapes, as well as the neighborhoods of other components. The rates of production and disintegration can vary over time or in dependency on their previous values. Multiple catalysts can be introduced, stationary or in flux with respect to each other. The influence of chance can be further amplified or totally removed (by extending the set of movement rules). The amount of matter in the system can be kept either constant or external inflows and outflows of substrate introduced. The system can be induced to disintegrate totally or to "freeze" into a stable allopoietic structure. Systems with turbulent behavior or only partially delineated membranes can be observed as well as the systems whose membranes are ever-expanding. Systems with broad or narrow membranes, substrate-seeking "amoebas" floating through space, and hundreds of other varieties can be evolved by adjusting and harmonizing a few parameters or rules.

We can even provide a connection between a particular structural adaptation and the change in the organization itself. The interacting rules, which are otherwise invariant, can be thus allowed to change according to appropriate meta-rules. Such self-affecting

systems are then capable of self-reproduction and therefore evolution.

We shall introduce a few simple experiments performed with the APL-AUTOPOIESIS model.¹³

4.1 Function and Form

We already discussed the distinction between systemic organization and structure. The same autopoietic organization is realizable through different structural forms although its basic unity of function and its identity as a unique system stay unchanged. Structural adaptations are triggered by specific perturbing changes in its environment. Maturana talks about structural coupling,⁷ i.e., "the effective spatio-temporal correspondence of changes of state of the organism with the recurrent changes of state of the medium while the organism remains autopoietic." This structural rapport of the system and its environment allows us to simulate complex structural histories, in a controlled and predictable way, without changing system's organization.

For example, such structural variables as size and shape can be simply studied. Changes in the catalytic neighborhood could elicit a large variety of structural responses, see some typical "snapshot" printouts in Figure 4.

Autopoiesis of a cell can be affected by a particular structural adaptation, its functions of production, disintegration and bonding affected to their extremes. An allopoietic structure, a crystal, might ultimately form. It can neither disintegrate nor expand or move. Either a weak catalytic reach or a high inflow of substrate could lead to such "allopoietization." On the other hand, an increased outflow of available substrate, creating disproportionately many holes, would cause the catalyst to move rapidly over the space and the turbulence of its neighborhood would prevent orderly bonding—no membrane may ever form.

One can simulate a growth in system's size quite simply by establishing a state-dependent change regime in the size of the catalytic neighborhood. Also, very complex shapes and patterns can be simulated as arising from structural adaptations of the autopoietic system. In Figure 5 observe an example of an autopoietic cell acquiring the shape of a cross. Theoretically, any complex shape can be induced to emerge through induced structural adaptations.

4.2 Biological Clock

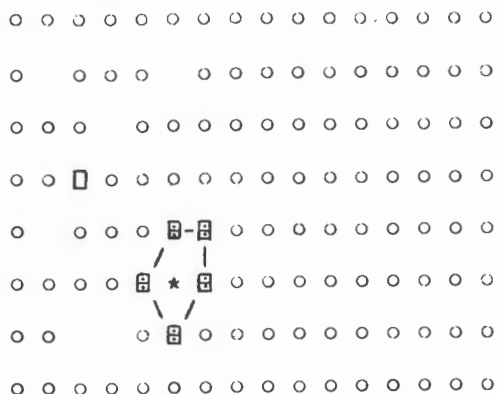
All living systems exhibit a variety of biorhythms and cyclical adaptations. The most prominent is the aging phenomenon, a clearly observable "life cycle" of growth, plateau and decline. Organizational stability and permanence of an autopoietic system is the permanence and stability of its structural history, not of its existence. All known autopoietic organizations have

"built-in death." They either crystallize into allopoietic debris or disintegrate back into their components.

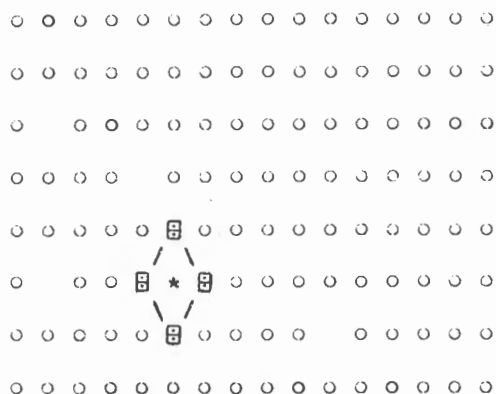
No autopoietic cell can escape death. Observe that it is unreasonable to assume that the catalyst is unaffected by its participation in the production of links. Each single act of production diminishes its catalytic

power. Initially, when there is a lot of free substrate, the number of produced links is naturally very high. At the same time, the number of holes necessary for disintegration is still very low. As a result there is a large initial build-up in the amount of organized matter (links, free or bonded). As the amount of free substrate

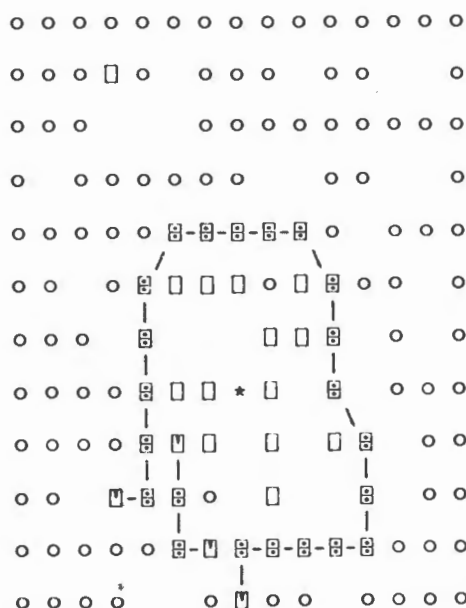
TIME: 20
HOLES: 6
RATIO OF HOLES TO SUBSTRATE: 0.0521
FREE LINKS: 1
ALL LINKS: 6



TIME: 35
HOLES: 4
RATIO OF HOLES TO SUBSTRATE: 0.0336
FREE LINKS: 0
ALL LINKS: 4



TIME: 34
HOLES: 34
RATIO OF HOLES TO SUBSTRATE: 0.2867
FREE LINKS: 14
ALL LINKS: 40
CUMULATIVE PRODUCTIONS: 58
PRODUCTIONS THIS CYCLE: 1



TIME: 16
HOLES: 33
RATIO OF HOLES TO SUBSTRATE: 0.183333
FREE LINKS: 14
ALL LINKS: 33

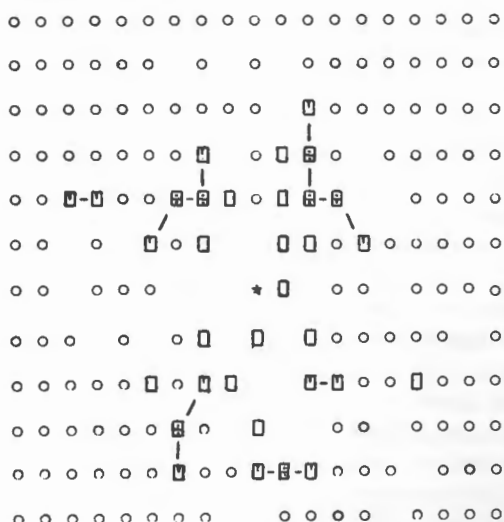


FIGURE 4 Illustrations of narrow, broad and shattered membranes. Both "crystallization" and "structural turbulence" are extreme manifestations of autopoietic adaptation.

TIME: 30
 HOLES: 48
 RATIO OF HOLES TO SUBSTRATE: 0.32
 FREE LINKS: 19
 ALL LINKS: 48

TIME: 32
 HOLES: 47
 RATIO OF HOLES TO SUBSTRATE: 0.309210
 FREE LINKS: 20
 ALL LINKS: 47

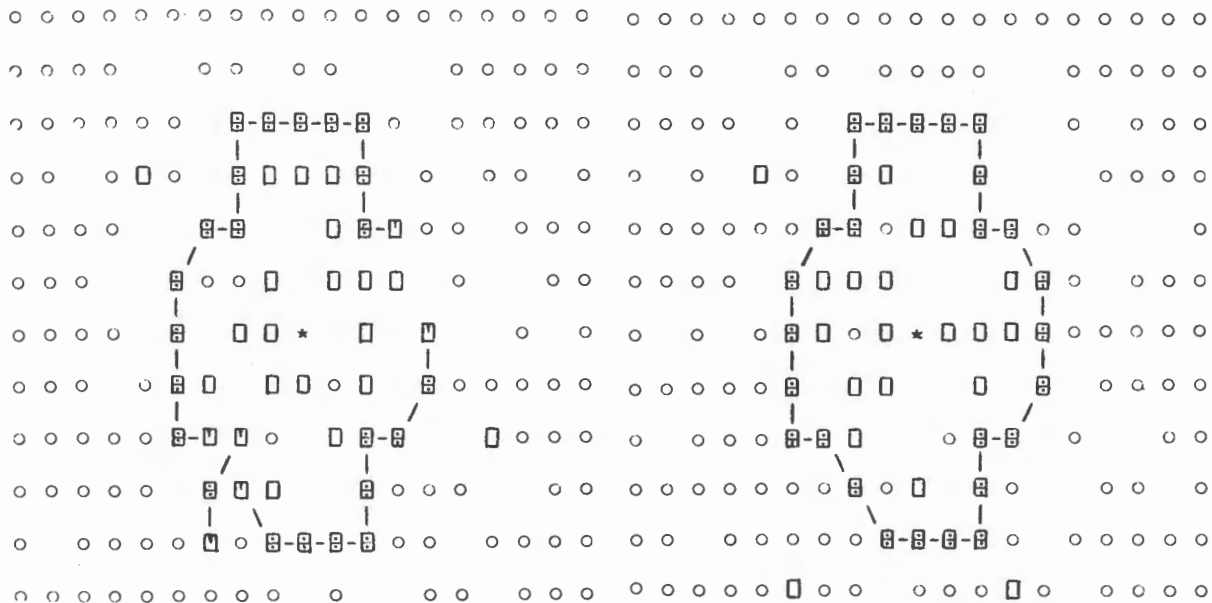


FIGURE 5 Shape of a cross-induced structural form of a membrane.

decreases and the number of holes increases, the two rates, production and disintegration, achieve a balance which is characteristic for a relatively stable period of self-repairing membraneous enclosure. But the production must go on, although at much slower rate, and the more productions are performed the weaker the catalyst becomes. Thus, we experience the fastest "aging" of the catalyst in the initial stages of the most vigorous production activity. Although this "aging rate" becomes progressively slower, the production rate is ultimately exceeded by the disintegration rate and the total amount of organized matter starts to decline. Because the holes become fewer again and there is more substrate available, the aging and loss of catalytic power speeds up at this later stage in a burst of activity before total catalytic exhaustion. The disintegration rate is already low before the death itself becomes only a slow decay afterwards.¹³

There is a large variety of other emergent rhythms that can be identified in the behavior of this autopoietic cell. For example, there is a natural cycle observed in the ratio of holes to substrate even when the rates of production and disintegration are kept stable. More substrate leads to more links and higher incidence of bonding. Consequently, the actual amount of substrate is less while the number of holes is up. That allows more links to disintegrate, creating more substrate and fewer holes again.

It would be a gross fallacy to interpret such structural rapport between the system and its environment as be-

ing due to some kind of a feedback mechanism. There is none. No information is transferred, none is coded. *It only appears as such to an observer.*

Multiple Catalysts

Obviously there can be any number of catalysts functioning in a given space. When they are distant enough they can enclose themselves quite independently and function without mutual interference. A group of autopoietic cells can be observed, each and all in a dynamic equilibrium with their environment.

The most interesting case arises if we assume that at a certain stage the catalyst is allowed to divide itself into two identical replicas. For example, the first total closure of a membrane provides the trigger which causes such catalytic replication. The new catalyst then occupies any immediately adjacent hole. Their respective neighborhoods overlap to a large extent. Note that a large portion of the original membrane will disintegrate because no re-bonding is possible in the area of the overlap. Because a catalyst cannot pass through bonded segments, it will ultimately float out of this new opening. The two catalysts of equal power will float apart and gradually enclose themselves by two separate membranes. The larger is the overlap of their respective neighborhoods, the stronger is this initial "pulling apart." Gradually they disconnect themselves, almost gently.¹³ See Figure 6.

Apparently a self-reproduction has occurred. There are two identical and independent autopoietic cells as a result of a simple mechanical division of a cell. A fairly close replica of the initial cell is obtained without the benefit of any copying, coding or information processing artifacts.

4.4 Autogenesis of Life: A Simple Scenario

We shall consider a uniformly distributed environment of basic particles of matter, •, devoid of any information and structure. Such universe is initially in a thermodynamic equilibrium. Let us assume that there is a separate locality where the local values of the mean density and temperature can differ from the equilibrium conditions. Only the particles • can penetrate the boundaries of such locality, both ways. All other structurally higher combinations of the basic particles are trapped inside the boundaries.

The following set of rules (one of many possible) would induce a self-organization of an autopoietic unity (like a living cell) independently of particular chemical and structural properties of the basic components:

- 1) • + • → • — •
- 2) • — • + • → • — •
- 3) • — • + • — • → • — •
- 4) • — • + • — • → • — •
- 5) ○ + • → ○
- 6) • — • + • — • → ○
- 7) • — • + • — • → ★
- 8) • — • + • — • → • — •
- 9) • — • + • — • → • — •
- 10) ★ + ○ + ○ → □ + ★
- 11) □ + □ → □ — □
- 12) □ — □ + □ → □ — □ — □
- 13) □ — □ — □ — □ — □ — □ — □ — □ — □ — □
- 14) □ → ○ + ○
- 15) □ — □ → ○ + ○
- 16) □ — □ → ○ + ○
- 17) ○ + ★ → ★
- 18) ★ + • → ★ + ★
- 19) ★ → ★ + ○

Observe that ultimately the density of substrate particles ○ increases as it might be necessary for a cell to emerge. At the same time both the stable, — and the unstable, • — •, compounds are being effectively trapped within the locality of disequilibrium. The chance of • — • + • — • → ★ is being steadily increased. When ★ emerges, one or more, the cell can be produced according to the rules we already studied. We can imagine that there are dormant and active layers of rules that are being brought to their action by the emergence of the necessary particles, molecules or compounds. Finally, the last three rules allow for "self-regeneration" of the catalyst and its replication. That triggers the autopoietic

division of the cell and induces self-reproduction.

Note that our fundamental particles, •, define space through their relationship and interaction. Thus space is only derived and an observer-dependent concept. It consists of a finite number of points in any of its neighborhoods and thus it is finite and discrete. Dirac suggested that space is filled with a sea of electrons occupying all energy levels up to the "Fermi level." The electrons which we observe have risen above the Fermi level, leaving behind a "hole," which is *observed* as a positively charged twin of the electron. The elementary particles of contemporary physics are continually emerging from and being reabsorbed into the "vacuum" of the Fermi sea. They are products of the underlying autopoiesis in the domain of fundamental substrate-particles.

5 Social Autopoiesis

The range of applications of autopoiesis is extending from atoms and molecules, organisms and nervous systems, language and communication, to social behavior, human societies, planning and management. At the same time the implications of autopoiesis are profound and often upsetting. The literature dealing with or related to autopoiesis is growing rapidly. We list some of the more important works in the References.¹⁸⁻³⁵

We conclude with some thoughts on social autopoiesis. Human societies, and any other societies of autopoietic components, can maintain their cohesiveness and unity through the "rules of conduct" that are spontaneously generated by the autopoiesis of the components. F. A. Hayek²¹ emphasized that the order of social events, though it is the result of human action, has not been entirely created by men deliberately arranging the elements in a preconceived pattern. If the forces or rules that bring about such spontaneous orders are understood, then such knowledge could be used to produce orders that are far more complex than those attempted by deliberately arranging all the activities of a complex society. This is not an argument against planning but rather against the simplistic tinkering and interfering with orders that are much too complex to be viewed as mechanical contrivances. S. Beer²⁹ also reiterates the fact that if a social institution is autopoietic then it is necessarily "alive," i.e., it maintains its identity in a biological sense.

Human systems, since they are not simple machines, should not be designed or analyzed. They should be managed. Manager is a catalyst of spontaneous social forces. Crystals are not produced by directly arranging the individual molecules, but by creating the conditions under which they form themselves. Plants or animals are not put together by designers. They are managed by inducing the conditions favorable to their growth. The task of human management is to stimulate a growth of network of decision processes, systems, programs and rules, i.e., an organization, which would be effective in attaining institutional objectives. Such growth process

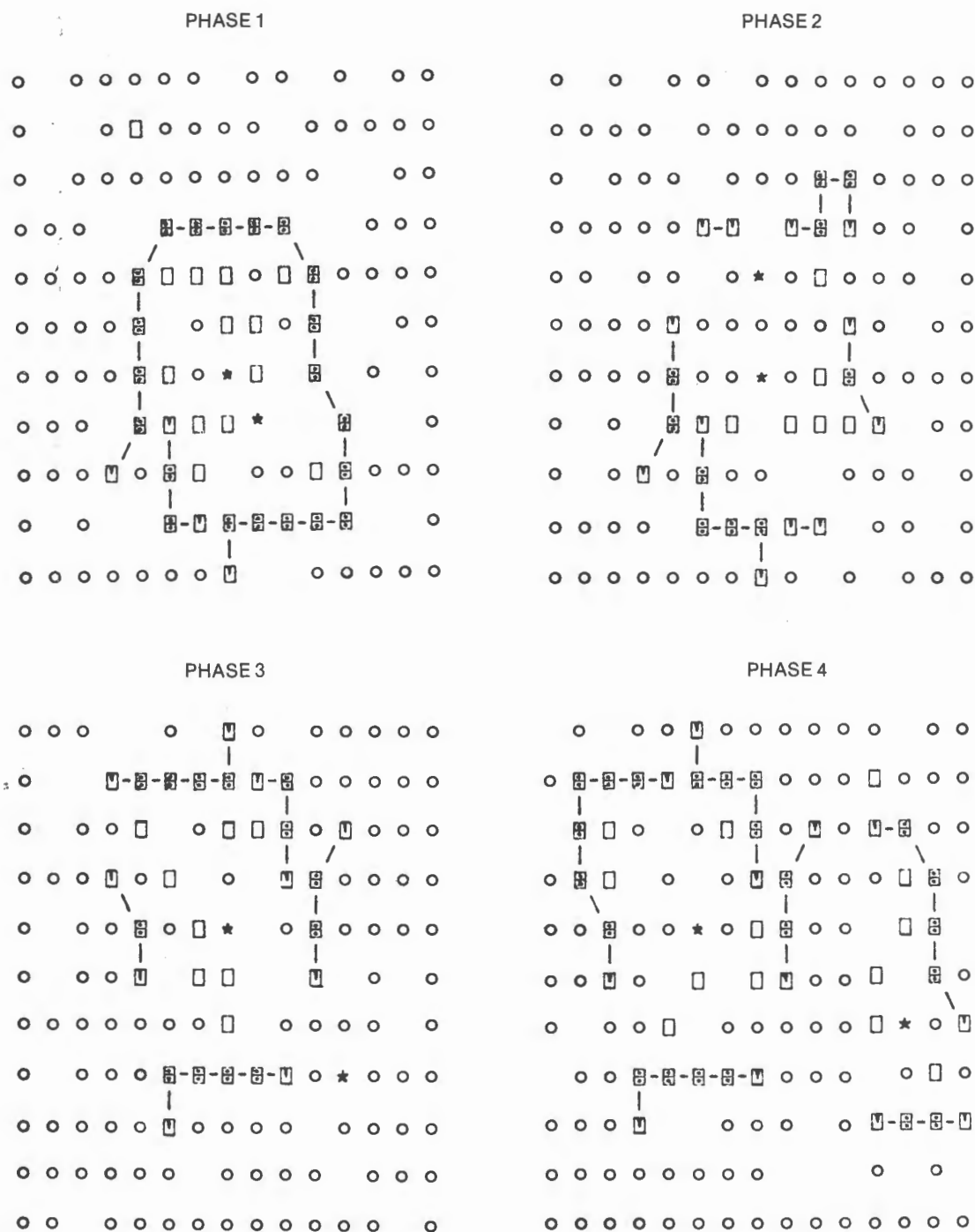


FIGURE 6 Multiple catalysts and the emergence of two distinct autopoietic unities.

of an autopoietic unity evolves its own rules of change. These rules, in turn, determine the kinds of structural adaptations which could emerge.

Humans *live* their lives through human systems, shape them through their *individual* aspirations, goals, norms and actions, which could be quite different and independent of the individual ones. Humans are in turn continuously being shaped by such self-organized entities, their spatial and temporal arrangement evolving through a succession of state determined structures. Human actions and interaction with their emerging

organization is irreducible to behavior, as it is so forcefully stated by E. Jantsch.³⁰

5.1 Human Systems Management

A new mode of inquiry into complex human systems is being evolved—Human Systems Management. It is based on the following set of observations:

- 1) Human systems are to be *managed* rather than

analyzed or designed. HSM is not systems analysis or design.

2) Management of human systems is a process of catalytic reinforcement of dynamic organization and bonding of individuals. HSM does not design a hierarchy of control and command.

3) The components of human systems are *humans*. HSM is not general systems theory but a general theory of *human* organizations.

4) The integral complexity of human systems can be lost through the process of mathematical simplification. They can be studied through a relatively simple set of semantic rules, governing the self-organization of their complexity. HSM is not operations research, econometrics or applied mathematics.

5) The interactions between individuals are not those of electronic circuitry, communication channels, or feedback loop mechanisms. HSM is not cybernetics or information theory of communication.

6) The order of human organizations is maintained through their structural adaptations under the conditions of environmental disequilibrium. HSM is not the theory of general equilibrium.

7) The concepts of optimization and optimal control are not meaningful in a general theory of human systems. Human aspirations and goals are dynamic, multiple and in continuous conflict. Such conflict is the very source of their catalysis. HSM is not optimal control theory or theory of conflict resolution.

8) The inquiry into human systems is *trans-disciplinary* by definition. Human systems encompass the whole hierarchy of natural systems: physical, biological, social and spiritual. HSM is not interdisciplinary or multidisciplinary, it does not attempt to unify scientific disciplines, it transcends them.

It is appropriate to conclude by quoting S. Beer:²⁹

"... the way an autopoietic system will respond to a gross environmental challenge is highly predictable—once the nature of its autopoiesis is understood. Clever politicians intuit those adaptations; and they can be helped by good scientists using system-theoretic models. Stupid politicians do not understand why social institutions do not lose their identities overnight when they are presented with perfectly logical reasons why they should; and these are helped by bad scientists who devote their effort to developing that irrelevant logic."

ACKNOWLEDGEMENT

I am grateful to Norbert Pierre for his valuable programming and computational assistance and to George Klir for his continuing encouragement and editorial support. Personal communications with Stafford Beer, Heinz von Foerster, Friedrich von Hayek, Erich Jantsch, Gordon Pask, Ricardo Uribe, Hugo

Uyttenhove and Francisco Varela were extremely stimulating and influential. This project was partially supported through the Faculty Research Grant of the Graduate School of Business at Columbia University.

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