

# SELF-ORGANIZATION OF LIVING SYSTEMS: A FORMAL MODEL OF AUTOPOIESIS

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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 the 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,<sup>1</sup> 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*,<sup>2</sup> Bogdanov's *Tectology*,<sup>3</sup> Leduc's *Synthetic Biology*,<sup>4</sup> Smuts' *Holism*<sup>5</sup> and von Hayek's *Spontaneous Social Orders*.<sup>6</sup>

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,<sup>7,8</sup> 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.<sup>9,10</sup>

A given system, observed as a distinct unity in its environmental 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 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.<sup>11-14</sup>

## 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.

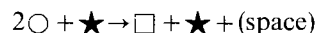
We shall designate the basic components of the model by the following symbols:

hole ( <i>H</i> )	(space)
substrate ( <i>S</i> )	○
free link ( <i>L</i> )	□

singly bonded link ( <i>B</i> )	◻ -
fully bonded link ( <i>B</i> )	- ◻ -
catalyst ( <i>C</i> )	★

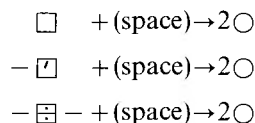
The original Varela-Maturana-Urbe model<sup>1</sup> was based on the following organization of components:

### 2.1 Production



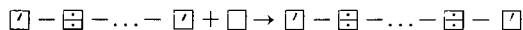
A catalyst and two units of substrate produce a free link and a hole, while the catalyst is assumed to be essentially unaffected by this operation. Production can take place when a pair of substrate is in the predetermined neighborhood of the catalyst. Catalytic "reach" or the strength of ★ and its dynamics 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.<sup>1, 13, 15, 16</sup>

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  $\star > \square > \circ > (\text{space})$  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,  $\square$ , single bonded,  $-\square$ , or fully bonded,

$-\square-\square-$ . Additional bonds,  $-\square-\square-$ , 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,  $\circ$ , 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*.<sup>17</sup>

An Abelian-group cellular automaton  $\Gamma$  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  $\Gamma$  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,<sup>36</sup> 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

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- 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  $t+1$ .

### 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  $\lambda_r$  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  $\lambda_r$ '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:

$$(i, j) + M_1 = (i-1, j) \\ (i-1, j) + M_3 = (i, j)$$

i \ j	1	2	3	4	5	6	7
1							
2				o			
3			o	o	o		
4		o	o	(i, j)	o	o	
5			o	o	o		
6				o			
7							

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.

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

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

$H(i, j) \equiv H(k)$  : hole (a quiescent state)

$S(i, j) \equiv S(k)$  : substrate

$L(i, j) \equiv L(k)$  : (free) link

$B(i, j) \equiv B(k)$  : bonded link

$C(i, j) \equiv C(k)$  : catalyst

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 for  $n \leq 3$ ,  $i, j \leq 2$ ,  $i, j \geq n-1$ , only *incomplete* neighborhoods can be defined. We shall state simple *boundary conditions*:

$$E(i, 2) + M_1 = E(i, 2) \\ E(2, j) + M_2 = E(2, j) \\ E(i, n-1) + M_3 = E(i, n-1) \\ E(n-1, j) + M_4 = E(n-1, j).$$

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  $N(k)$ :

- i) select a direction  $M_r$  and a number of steps  $\lambda_r$ , and then identify the state of  $(k + \lambda_r M_r)$ .
- ii) 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

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

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  $H(M_r + M_r)$ , 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.

$$H, H(R_r) \rightarrow H, H(M_r)$$

$$H, S(R_r) \rightarrow S, H(M_r)$$

$$H, L(R_r) \rightarrow L, H(M_r)$$

$$H, B(R_r), S(2M_r) \rightarrow S, B(M_r), H(2M_r)$$

$$H, C(R_r) \rightarrow C, H(M_r)$$

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,

$$L, L(R_r) \rightarrow L, L(M_r)$$

$$L, B(R_r) \rightarrow L, B(M_r)$$

$$L, C(R_r) \rightarrow L, C(M_r)$$

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:

$$L, S(R_r), H(M_r + R_H) \rightarrow H, L(M_r), S(M_r + M_H)$$

$$L, S(R_r), B(M_r + R_B), H(M_r + 2M_B) \rightarrow$$

$$H, L(M_r), B(M_r + M_B), S(M_r + 2M_B)$$

$$L, S(R_r) \rightarrow S, L(M_r)$$

$$L, H(R_r) \rightarrow H, L(M_r)$$

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,

$$C, B(R_r) \rightarrow C, B(M_r)$$

$$C, C(R_r) \rightarrow C, C(M_r)$$

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

$$C, L(R_r), S(2M_r), H(2M_r + R_H) \rightarrow$$

$$H, C(M_r), L(2M_r), S(2M_r + M_H)$$

$$C, L(R_r), S(2M_r), B(2M_r + R_B), H(2M_r + 2M_B) \rightarrow$$

$$H, C(M_r), L(2M_r), B(2M_r + M_B), S(2M_r + 2M_B)$$

$$C, L(R_r), H(2M_r) \rightarrow H, C(M_r), L(2M_r)$$

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

$$C, S(R_r), H(M_r + R_H) \rightarrow H, C(M_r), S(M_r + M_H)$$

$$C, S(R_r), B(M_r + R_B), H(M_r + 2M_B) \rightarrow$$

$$H, C(M_r), B(M_r + M_B), S(M_r + 2M_B)$$

$$C, S(R_r) \rightarrow S, C(M_r)$$

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:

$$C, L(R_r), B(2M_r) \rightarrow L, C(M_r), B(2M_r)$$

$$C, L(R_r), L(2M_r) \rightarrow L, C(M_r), L(2M_r)$$

$$C, L(R_r), C(2M_r) \rightarrow L, C(M_r), C(2M_r)$$

and also

$$C, H(R_r) \rightarrow H, C(M_r).$$

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

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

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,  $X_S \in W_S = \{X_S \mid S(X_S)\}$ , 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.,

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

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

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

as the set of pairs of operators leading to adjacent

i \ j	1	2	3	4	5	6	7
1							
2							
3				●	●	○	
4			○	★		○	
5				●	●		
6							
7							

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

pairs of substrates. As an example, consider the situation in Figure 3, where

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

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:

$$C, S(R_{S1}), S(R_{S2}) \rightarrow C, L(X_{S1}), H(X_{S2})$$

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:

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

and

$$T_2 = \left\{ M_{S2} \mid S(M_{S2}) \cap \left[ \bigcup_{i=S2-1}^{S2+1} B(M_{S2} + M_i) \cap H(M_{S2} + 2M_i) \right] \right\}$$

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  $\alpha$ 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  $K_B$ :

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

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  $\alpha < \beta$  and  $\bar{R}_B = (R_{B1}, R_{B2})$ :

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

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

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

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:

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

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

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

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

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

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

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

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

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

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

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

where  $Z''_B$  determines pairs of singly bonded links which can be bonded. Let us define the following set:

$$\{ X_e \mid \bar{X}_{Bi} \cap \bar{X}_{Bj} = X_{B=e} = X_e \},$$

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

$$B^z(X_{B1}), B^\beta(X_{B2}) \rightarrow B^z(X_{B1}), B^z(X_{B2})$$

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

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

where  $X_L$  is derived as follows:

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

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 the 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.<sup>13</sup>

#### 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,<sup>7</sup> 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 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

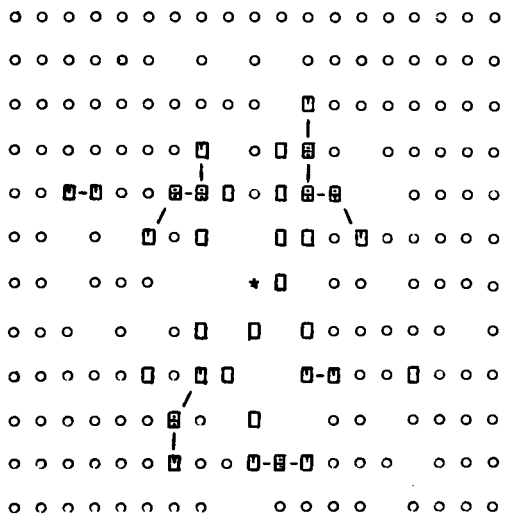
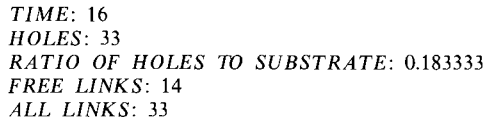
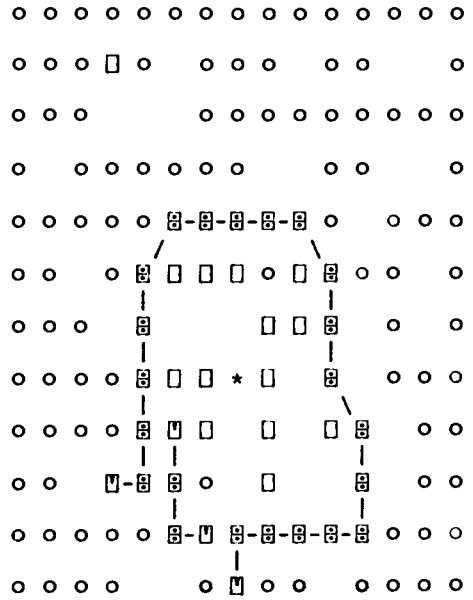
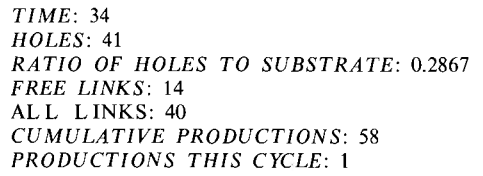
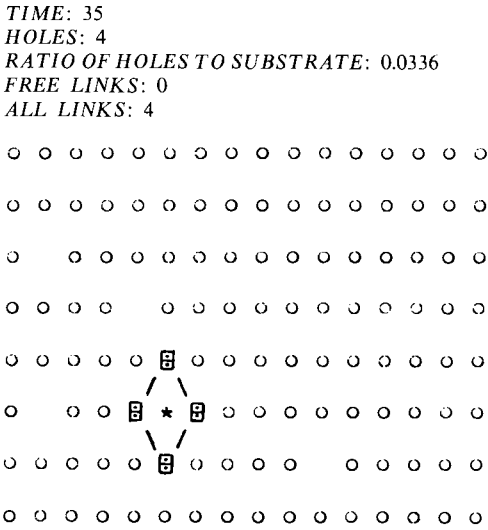
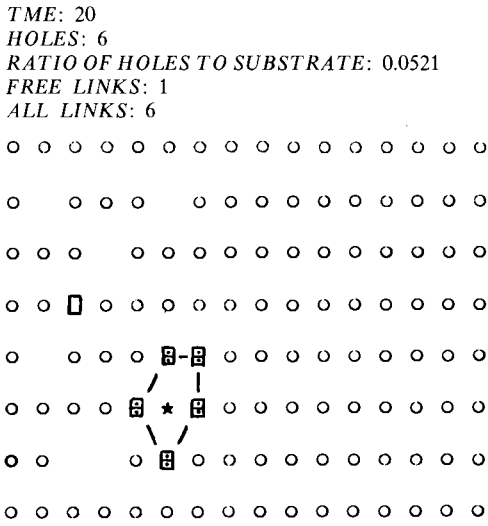


FIGURE 4 Illustrations of narrow, broad and shattered membranes. Both "crystallization" and "structural turbulence" are extreme manifestations of autopoietic adaptation.

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

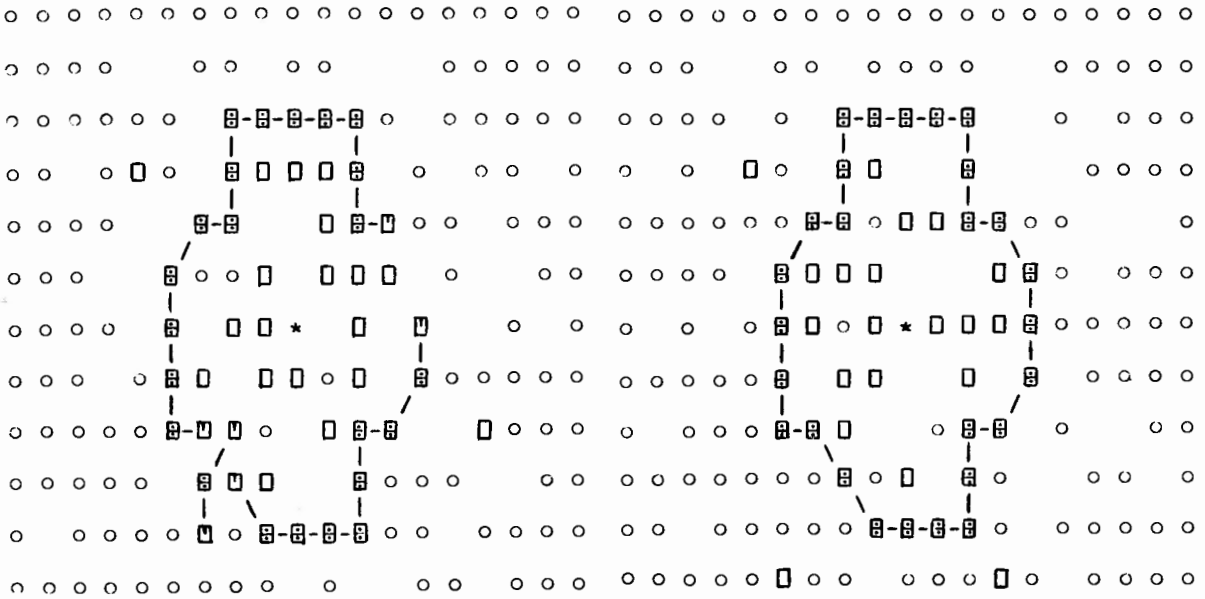


FIGURE 5 Shape of a cross-induced structural form of a membrane.

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 and becomes only a slow decay afterwards.<sup>13</sup>

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 being 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.<sup>13</sup> 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) • - • + • →  $\begin{matrix} \vdots \\ \vdots \end{matrix}$
- 3) • - • + • - • →  $\begin{matrix} \vdots \\ \vdots \end{matrix}$
- 4) • - • +  $\begin{matrix} \vdots \\ \vdots \end{matrix}$  → ○
- 5) ○ + • → ○
- 6)  $\begin{matrix} \vdots \\ \vdots \end{matrix}$  + • - • → ○
- 7)  $\begin{matrix} \vdots \\ \vdots \end{matrix}$  +  $\begin{matrix} \vdots \\ \vdots \end{matrix}$  → ★
- 8)  $\begin{matrix} \vdots \\ \vdots \end{matrix}$  + • → • - • + • - •
- 9)  $\begin{matrix} \vdots \\ \vdots \end{matrix}$  + • →  $\begin{matrix} \vdots \\ \vdots \end{matrix}$  + • - •
- 10) ★ + ○ + ○ → □ + ★
- 11) □ + □ → □ - □
- 12) □ - □ + □ → □ - □ - □

- 13) □ - □ - ... - □ + □ → □ - □ - ... - □ - □
- 14) □ → ○ + ○
- 15) - □ → ○ + ○
- 16) - □ → ○ + ○
- 17) ○ + ★ →  $\begin{matrix} \vdots \\ \vdots \end{matrix}$
- 18)  $\begin{matrix} \vdots \\ \vdots \end{matrix}$  + • → ★ + ★
- 19)  $\begin{matrix} \vdots \\ \vdots \end{matrix}$  → ★ + ○

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,  $\begin{matrix} \vdots \\ \vdots \end{matrix}$  and the unstable,  $\begin{matrix} \vdots \\ \vdots \end{matrix}$ , compounds are being effectively trapped within the locality of disequilibrium. The chance of  $\begin{matrix} \vdots \\ \vdots \end{matrix}$  +  $\begin{matrix} \vdots \\ \vdots \end{matrix}$  → ★ 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.<sup>18-35</sup>

We conclude with some thoughts on social autopoiesis. Human societies, and any other soci-

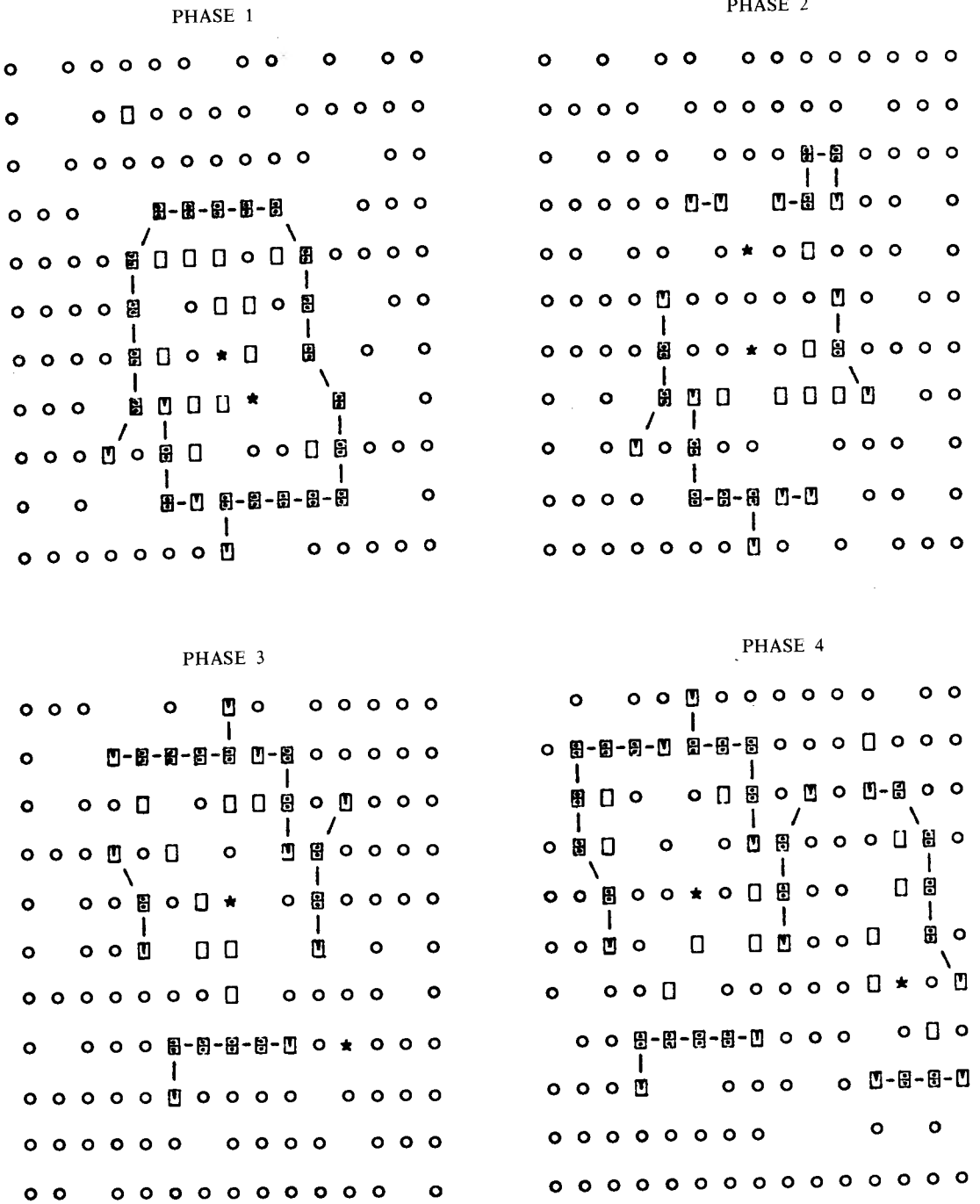


FIGURE 6 Multiple catalysts and the emergence of two distinct autopoietic unities.

eties 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. Hayek<sup>21</sup> 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. Beer<sup>29</sup> 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 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, creating a set of systemic 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.<sup>30</sup>

### 5.1 Human Systems Management

A new mode of inquiry into complex human systems

H

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 *transdisciplinary* 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:<sup>29</sup>

“... 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."

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