SELF-ORGANIZATION AND STOCHASTIC RE-CAUSALIZATION IN SYSTEM DYNAMICS MODELS

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Abstract

Self-organization denotes a class of instabilities in which a system spontaneously generates structure, diversity and/or specialization. From a thermodynamic point of view, transitions of this kind, which proceed against the general tendency for relaxation towards an unstructured equilibrium, can occur in energetically open systems and under far-from-equilibrium conditions. The exergy required to build up and maintain a non-equilibrium (so-called dissipative) structure can here be extracted from the continuous supply of energy (and/or resources).

The interest in self-organizing systems originates in the work on irreversible thermodynamics performed primarily by the so-called Brussels school. According to this school, developments in biological, ecological and social systems which involve qualitative change, diversification or increased complexity are also to be viewed as self-organizing processes. This applies for instance to the build-up of genetic information, the appearance of new species in an ecological system, the introduction of new techniques in a social system, the adoption of new scientific paradigms, and the penetration of new products.

In the present paper we analyse the basic ideas of self-organization in terms of concepts familiar to System Dynamics practitioners. Through a series of relatively simple models it is shown how System Dynamics can be used as an efficient tool for modeling self-organizing systems. As a particular example we consider the evolution of cooperative structures (RNA molecules with their associated enzymes) in a prebiotic system.

Introduction

Is the American society stable with respect to a social or racial revolution? If the unemployment was to increase would there be a kind of threshold value above which the society becomes unstable, and a nationwide upheaval can be triggered by almost any outbreak of local unrest.

These questions belong to a type that System Dynamics practitioners are not so used to consider. Nontheless, they appear to be quite relevant in discussing the possible future developments of USA and, more particularly, for assessing the limits to a contractive economic policy.

On this background, one may ask if human societies are operating under such conditions that they are unstable with respect to certain small disturbances. And the answer to this question is clearly: yes, sometimes. The human population, for instance, may be unstable with respect to the spread of vira or bacteria from laboratories engaged in genetic engineering or production of biological weapons. In 15-20 years, when less than half of the population has been vaccinated, the human race may be unstable with respect to the reappearance of smallpox. This implies that a local outbreak of this disease could explode into a major epidemic wave which would propagate all around the world. Even more frightful, the terror balance may some day turn out to be unstable with respect to a small disturbance in the Middle East, or even in the electronic warning systems.

These examples give an impression of what is meant by instabilities in social systems. All the examples may be considered as relaxation type transitions, however, which can occur in isolated systems. The main idea of Prigogine and his co-workers(1,2) is that human societies are open systems in

which large amounts of energy and resources are processed. These flows of exergy (useful energy) so to speak "lift" the systems far away from equilibrium and permit "upward transitions" in which structure is created, and diversity and specialization spontaneously increased. The evolution of social systems is thus to be considered as a series of instabilities leading to an increasing level of complexity.

This is presumably a rather unfamiliar viewpoint to many system dynamicists. It also appears to conflict with the usual assumptions about the stability of social systems. With the present paper we would like to show how the notion of self-organization can be accomodated within System Dynamics, and also to illustrate how System Dynamics can be used as a tool for modeling unstable transitions. The contention that social systems are stable to parameter fluctuations is a practical working hypothesis in many situations. It is not a scientific fact, however, and by incorporating the ideas of the Brussels school, system dynamicists can complement their understanding of evolving social systems.

There may be some semantic problems(3), as there will often be when ideas from different disciplines are brought together. In particular, the word structure as applied by the Brussels school usually refers to the spatial and/or temporal variation of a distributed system. Therefore, self-organization in irreversible thermodynamics does not necessarily imply a change in the basic equations of motion, or in the logical structure as represented by the System Dynamics flow-diagram.

However, in the hierachy of successive bifurcations leading to different dissipative structures in a hydrodynamic system, for instance, the equations of motions to be used may change completely from level to level. Then, we have also a change in the logical structure. If we want to apply the idea to social systems, the self-organizing transitions must be represented as activations of various parts of or causal relations in a flow-diagram. It is important to notice, however, that this activation occurs through a spontaneous process, i.e. as a result of certain noise components becoming unstable.

An alternative process in which hidden parts of a flow-diagram are activated when certain conditions are satisfied by the system's macroscopic variables has been investigated by Barry Richmond(4). We have extended this work by assuming the activation of certain causal relations to be determined stochastically, and by introducing auxiliary conditions which evaluate the performance of the system and, for instance, stabilize particularly advantageous connections. We would like to refer to such a process as "stochastic re-causalization". It does not describe the spontaneous transitions associated with self-organization in detail. Under certain conditions it may be a reasonable approximation, however, which allows one to handle systems in which a large number of transitions are possible.

Self-organizing processes in nature

Self-organization is the thermodynamic term for a class of processes by which a system under far-from-equilibrium conditions spontaneously develops spatial structure and/or breaks into sustained oscillations. Light amplification by stimulated emission of radiation (Laser-action) is a typical example of self-organization. When a gas (a glass or a semiconductor) is pumped sufficiently above thermal equilibrium by illumination for instance with ultraviolet light, it may suddenly break into a qualitatively different mode of behaviour in which the emitted spectrum of incoherent light is replaced by a single line of sometimes extreme coherency. This transition occurs because, above a certain pumping threshold, particular components of the system's random noise become unstable and start to build up exponentially until after many decades of amplification they are finally limited by non-linear processes.

Another example of a self-organizing process is the Bénard instability(6). A few mm thick layer of oil in a pan is heated uniformely from below. As long as the temperature difference between the top and the bottom of the layer is sufficiently small, heat is transported up through the layer by conduction. If the heating is intensified, however, at a certain well defined temperature gradient, regular macroscopic convection cells spontaneously appear(7). A transition has here occurred in which convection currents representing a high degree of organization have grown out of irregular molecular motions or occasional hydrodynamic disturbances.

The more detailed mechanism involved in the Bénard instability is not so difficult to understand. It is related to the decrease of the surface tension of a liquid with increasing temperature. Thus if for instance the temperature of a certain small area of the surface by a random fluctuation happens to be higher than elsewhere, oil is drawn away from this area along the surface. To replace it, oil will start to rise from below. The rising oil is warmer than the surface oil, however, and the local increase in surface temperature will therefore be enhanced. This establishes a positive feed back which in the end leads to the formation of macroscopic convection cells. A threshold for the temperature gradient exists because the convection currents must overcome the friction associated with the finite viscosity of the oil.

There is no reason to dwell too much with this example, however, because we all know of self-organizing processes in our daily lives: the growth of snow crystals, the development of frostwork on our windows at wintertime, the formation of sand bars along a beach, the generation of characteristic washboard groves on top of the sand bars, the division of the earth's atmosphere into belts of opposite wind directions, and the formation of low-pressure cyclons, just to mention a few. None of these phenomena can be described on a purely deterministic basis because they originate in small irregularities which by virtue of an instability have grown into coherent macroscopic patterns.

Besides in lasers, self-organizing processes are technically employed in microwave generators, Gunn diodes, multivibrators, etc. In our more technically oriented research, two of us have been engaged with the study of self-

organizing effects in connection with diffusion of surface tension active molecules through liquid-liquid interfaces and instabilities of cell membranes (8,9), and with the formation of acoustoelectric high field domains (1o,11).

The contribution that the Brussels school has made to the field (besides introducing the term self-organization) is mainly to establish the common thermodynamic principles for these far-from-equilibrium processes. At the same time, the Brussels school has generalized the idea by postulating that similar processes play a vital role in the evolution of biological, ecological and social systems. From the thermodynamic point of view, the most fundamental features of such systems are the unidirectional transformation of large amounts of food or fuel of medium grade energy content into low grade waste (entropy) coupled with a simultaneous build-up of high-exergy structures. Through the degradation of resources, the systems - in stead of relaxing towards a state of thermal equilibrium where no life is possible - become capable of building up and maintaining a high degree of complexity. This is merely a restatement of the second law of thermodynamics, and the way such systems restructure themselves through non-linear interactions of sociological, economical or psychological nature, can be seen as an illustration of the concept of dissipative structures.

In this way, self-organization becomes a paradigm of evolution through instabilities, a paradigm which complements the more mechanistic view of classical System Dynamics.

It is also possible that self-organization can occur in a model which unintendedly becomes unstable to computational noise. We shall not enlarge on this problem, however, but rather try to show how self-organizing processes can be handled with System Dynamics.

As easy as lifting a feather

November 7, 1917 is presumably one of the most significant dates(12) in modern history. This was the day when Lenin and his bolschevists took power in the Russian Capital Petrograd. Eight months before, the Zar regime had stopped to function. On top of centuries of impoverishment and injustice, the enormous problems associated with the war had strained the system above a critical threshold. The population had revolted all over the country, and the soldiers had refused to fight.

The fall of the Zar regime left a political vacuum. Officially, the country was ruled by a provisional government, but the authority of this government was very limited. In these months, the political scene was dominated by liberals and socialists who hoped for the rise of a decentralized and democratic society. But the population was impatient: "The revolution has already lasted for 6 weeks, and nothing has changed", wrote dissatisfied peasants to the government. Workers, soldiers and farmers formed soviets, committies and councils. Hitherto forbidden political parties started a hectic campaign to prepare for the election of a constituent assembly, and national minorities raised demands for home-rule and independence.

Under these conditions, the bolschevists could take power through a minor operation involving armed workers and soldiers from the garrisons in Petrograd, and within a few days a new government had been established with the promises of "pease" and "bread". "It was as easy as lifting a feather", Lenin is reported to have said. (The real build-up of a new power structure was a tremendous task which lasted decades rather than days, and in which terror and civil war were significant tools).

It is not our purpose in the present paper to discuss a model of the Russian revolution. Rather, we would like to use some af the characteristic elements of the revolutionary process to illustrate unstable transitions in social systems. These elements are:

(1) the sudden break-down of an apparently stable structure when strained above a critical level,

(2) the creation of a "vacuum" in which several rivaling, more or less organized activities explode, and

(3) the rather unexpected appearance of a new dominant power which suppresses all alternatives.

As we shall show it is quite possible to represent these elements in a System Dynamics model.

The flow diagram of figure 1 shows a schematic representation of the basic elements of an unstable social process. As long as the indicator of social tension IST is below a certain threshold value (threshold for social tension THST), the system is in stable equilibrium in a state in which the whole population of 20 million people is politically indifferent (politically indifferent persons PIP). Indeed there is always a small generation of political activists, but under normal conditions their number is vanishing small. As examples of such activists, the model considers left wing extremists LWE, moderate political activists MPA, and right wing extremists RWE.

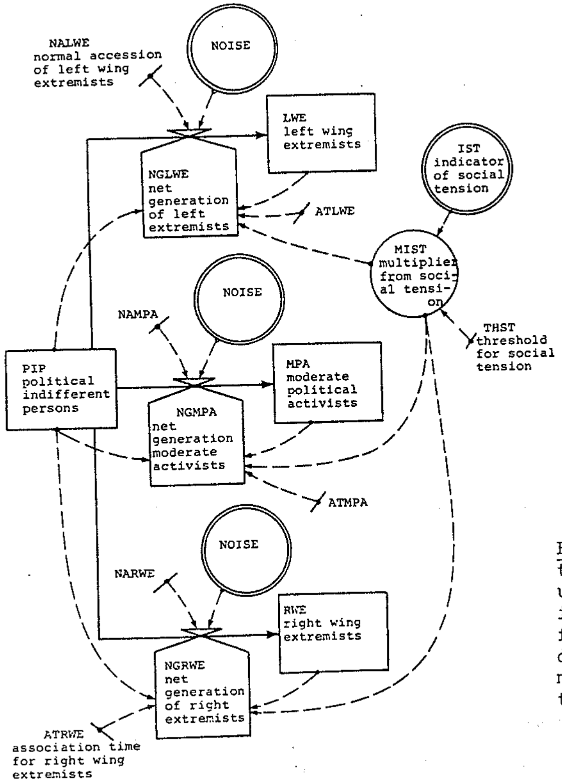

Figure 1. To illustrate the basic ideas of unstable transitions in social systems, this figure shows the flow-diagram of a schematic model of social revolution.

The generation of political activists is represented by the three rate variables: net generation of left wing extremists NGLWE, net generation of moderate political activists NGMPA, and net generation of right wing extremists NGRWE. Each of these rate variables has a random accession term proportional to the normal accession rate, and to the fraction of remaining political indifferent persons. There is also a defection term which is modelled as a relaxation process, i.e. it is proportional to the number of activists of each kind divided by the corresponding average association time. Together these two mechanisms produce a "back-ground noise" of activists of the order of a few thousands.

If the indicator of social tension IST becomes larger than the threshold value THST, the system is no longer stable in its original (ground) state, but positive feedback loops are activated which generate an exponentially rising number of activists in each of the three groups. There is now a characteristic incubation period before the number of activists has grown by the 3-4 orders of magnitude necessary for it to become comparable with the total population. When this occurs, however, the non-linearity associated with the total number of people being constant sets in, the exponential growth ceases, and one group of activists become dominant. Which group that is going to win depends crucially upon the parameters used to specify the random accession rates, the defection rates, and the reinforcing positive loops.

The DYNAMO-program for the simple model of a social revolution is given in the appendix. Figure 2 shows a characteristic simulation result. The indicator of social tension (which in general could be defined as an endogenous variable) has here been taken to increase linearly from 0 to 2 during the first 20 time units, and hereafter to remain constant. The system then becomes unstable at time 10. After an incubation period of 7-8 time units, the number of activists become large enough to be distinguished from zero on the DYNAMO-plot. The number of political indifferent persons then drops dramatically, and after a short struggle the moderate political activists take over the political scene.

Figure 3 shows similar results only with the modification that the average association time for left wing extremists has been increased from 2 to 3 time units. This relatively small parameter change is sufficient for the left wing extremists to become completely dominant.

The above model is an idealized model of a self-organizing process. With a few modifications it could represent for instance the growth of modes in a laser above the pumping threshold. For a distributed system in which the self-organizing process produces a spatial structure, the three level variables would represent amplitudes or intensities of various spatially defined eigen-functions. Our model could also serve as a kind of switching module in a larger System Dynamics model, i.e. as a module which driven by the occurrence of instabilities would activate various causal relations or hidden parts of a flow-diagram.

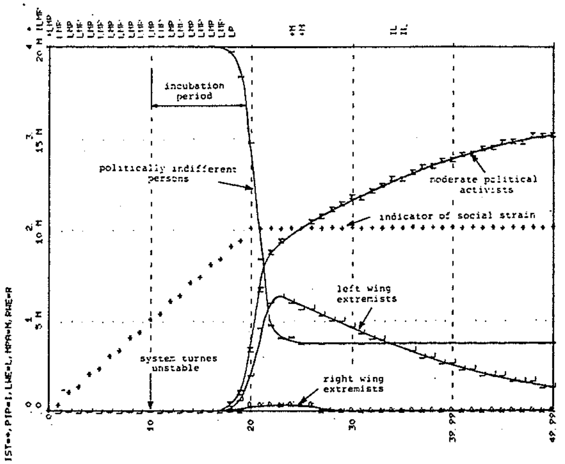

Figure 2. Simulation results obtained with the schematic model of social revolution. In this run the moderate political activists are seen to win.

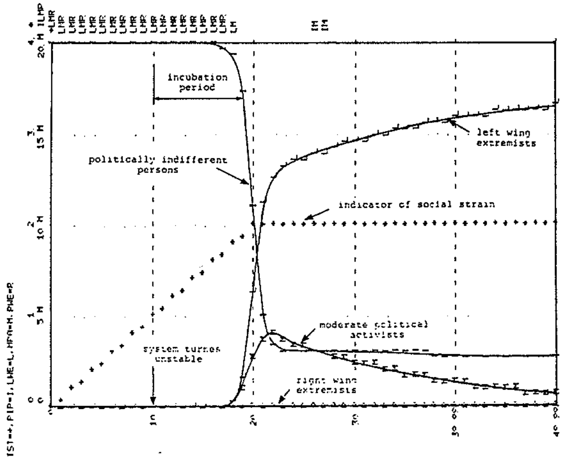

Figure 3. Same as figure 2 except that a relatively small parameter change now leads to the result that left wing extremists take power.

Self-organization in a mutating two-species system

Self-organization can occur under somewhat different conditions with respect to the noise amplitude. In the simple model of a social revolution discussed in the preceding section, the background noise of political activists was relatively strong, and as a consequence the outcome of the revolutionary process was mainly determined by the strength of the positive growth loops. As an example of the opposite situation we shall now consider a system which is unstable from the very beginning, but for which the self-organizing transition is triggered by a relatively infrequent random event. Under these conditions there is a considerable uncertainty with respect to when the transition will occur.

Figure 4 shows the flow-diagram for an ecological system in which a population of species A is in equilibrium with a resource pool RES. To indicate that we are considering an open system, there is a continuous in- and out-flow of resources as modeled through the rate-variables RIF (resource in-flow) and ROF (resouce out-flow). There is also a resouce usage rate RUR which is proportional to the number of species A NA and to the individual resource consumption MCA (metabolic constant for species A). The specific resource availability SRA, i.e. the amount of resources per unit of population influences the net growth rate for species A NGRA. In particular, there is a characteristic value of SRA above which the growth rate turns positive.

However, the system also includes the infrequent but possible event of a mutation by which an individual (or a pair) of species A is transformed into species B. Everything

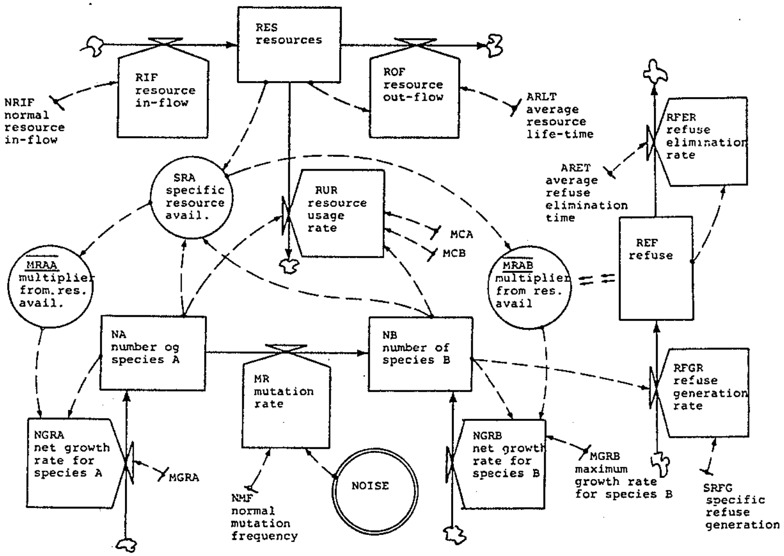

Figure 4. Flow-diagram for a unstable ecological system. With the self-organizing transition being triggered by a relatively infrequent mutation, there is a considerable uncertainty with respect to when the transition occurs.

that has been said about species A also holds for species B, except that individuals of species B are assumed to have a better resource utilization. As a result the population of species B can maintain a positive net growth rate and reduce the resource pool at a value of the specific resource availability SRA which is too small for the population of species A to grow. The system is thus unstable in its initial state. If a mutation occurs, the system performs a transition from its original state into a new state in which the population of species B is in equilibrium with the resource pool, while population A is extinguished.

The occurrence of a mutation can be expressed as(13,14)

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MR.KL=CLIP(0,1,NNAB.K,NMF.K*NA.K*DT)
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NNAB.K=NOISE()+.5 is here a random number uniformely distributed between 0 and 1. NMF is the normal mutation frequency, and NMF.K*NA.K*DT thus gives the probability that a mutation will occur in the time-step DT. The CLIP-function compares the random number with the probability for a mutation to occur, and if NNAB.K happens to be smaller than the mutation probability, this is taken to mean that a mutation does occur (15).

Figures 5 and 6 show the simulation results obtained with two different initiations of DYNAMO's noise-function. The initial population of species A is 4000, and the normal mutation frequency is $2\cdot10^{-5}$. In figure 5, the mutation occurs before time 20 while in figure 6 the mutation does not occur until about time 45. This illustrates the sensitivity of an unstable macroscopic system (thousands of individuals) to a small random fluctuation. As shown in the flow-diagram of figure 4, we have extended the model a little by assuming that species B produce a refuse at a rate which is proportional to the population size. The model also assumes that the produced refuse is eliminated with a certain characteristic time constant ARET. Figures 5 and 6 show how the refuse (or waste) builds up in the two simulation runs.

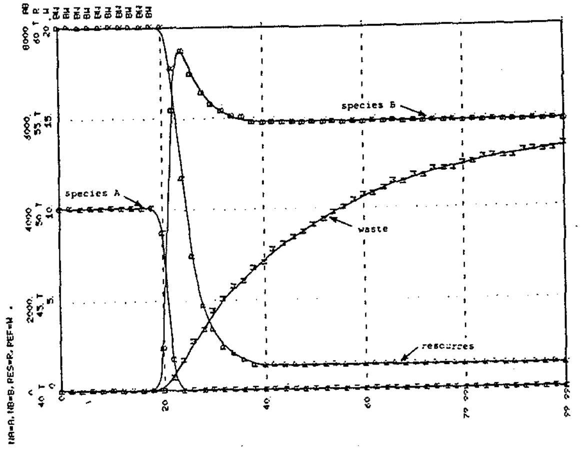


Figure 5. Simulation results obtained with the model of a mutating two-species system. The self-organizing transition occurs at time 18.

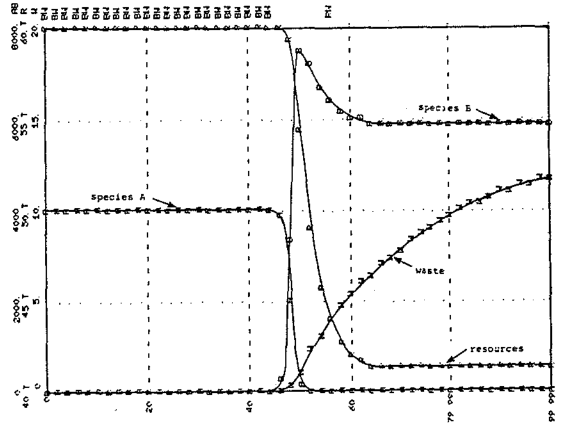


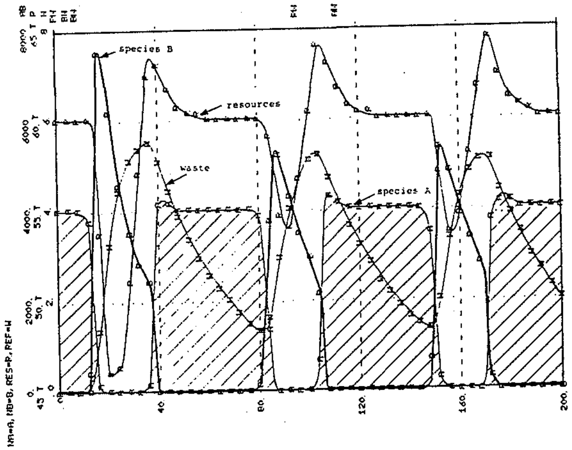
Figure 6. Same as figure 5 except that the simulation has been run with another initiation of DYNAMO's noise-function. The transition now occurs at time 45.

The above process is an unstable transition. One species competing another species away from the scene is not <u>per se</u> a self-organizing processes, however. This requires in general the emergence of additional species and/or the division of function (creation of niches). It might be though that species B have a higher degree of internal sophistication than species A, and that the level of complexity for the system is increased in this way.

It is also possible, however, to make the system perform a self-organizing transition which is more similar to the dramatic change in the mode of behaviour which characterizes self-organizing processes in thermodynamic systems(16). To do this we only have to add the assumption that the metabolic biproducts (refuse) produced by species B with a certain delay become poisonous to this population. (The corresponding causal relation is indicated with four small arrows in figure 4, the total DYNAMO-program can be found in the appendix). When a mutation occurs, the system now transfers from its original stationary state into a self-sustained strongly nonlinear oscillation (a limit cycle). This is illustrated in figure 7. When looking at this figure it should be recalled that the dramatic macroscopic oscillations in the bi-stable system are the result of the mutation of one single individual.

Information crisis in a prebiotic system

The most fascinating of all self-organizing processes is the development of life out of the simple organic and inorganic compounds of primordial world. Exactly how things happened when life began some 3 billion years ago is not known, but we have some general conceptions about the kind of processes which took place, and the conditions under which they occurred. It is very clear that the evolution must have faced several severe information crises in which new principles of organization had to be found to protect the information already developed and to make continuation of the information build-up possible. One such crisis was solved through the development of cells, but even before that time the development of sufficiently long RNA-molecules had to find a solution.



<u>Figure 7</u>. Self-sustained oscillations in the macroscopic two species system upon the mutation of one single individual of species A into species B.

Even at the molecular level, the evolution of life can be interpreted in terms of Darwinian principles of natural selection. It is a trial and error process in which a wide spectrum of randomly produced structures are tested with respect to their ability to survive under the given conditions (17,18). For simple molecules, the "competition" is a question of rate constants in the formation process and resistance to decomposition.

A basic step in the evolutionary process was the development of self-replicating RNA-molecules. (The appearance of DNA presumably occurred at a somewhat later stage). This introduced a first order autocatalytic process or, in System Dynamics terms, a positive feedback in the generation process. RNA-molecules are threadlike structures build up as chains of nucleotides. Each nucleotide consists of a sugar, a phosphate compound and a nitrogen containing organic base. The sugars and phosphates are linked together to form the "back-bone" of the molecules, while the genetic information is encoded as a particular sequence of the four possible, pairwise complementary bases.

In a replication process, the string of nucleotides serves as a template along which complementary nucleotides are assembled according to the base pairing rules. With catalyzing effects from various inorganic compounds and from miscellaneous primitive proteins, chemical forces and thermodynamic laws permit the formation of RNA strings with up to about 100 nucleotides, corresponding may-be to today's transfer RNA-molecules. At this stage, the information build-up is terminated by inevitable errors in the replication pro-

cess. However, the information carried by such RNA-molecules is not sufficient for them to produce more specific proteins, and without the enzymatic effects of such proteins, the necessary error suppression in the replication process can not be achieved.

To overcome this "crisis" and make possible the production of RNA-molecules with several thousands of nucleotides, a new principle of organization had to be developed. Eigen (17,18) has suggested that this was acomplished through the formation of cooperative structures (so-called hypercycles) between different RNA-subsystems. Such a hypercycle would result if one type of RNA-molecule by chance happened to produce a protein which could facilitate and stabilize the production of another type of RNA-molecules, and if at the same time the second type of RNA-molecules produced a protein which could assist the replication of the first RNA-molecules.

In the beginning, such a narrow closed loop would probably not have occurred. Rather, the simple proteins produced by a given type of RNA-molecules would be relatively unspecific and would catalyse the replication of a great many other molecules. Other types of RNA-molecules might also start to produce relatively unspecific, slightly enzymatic proteins, and at a certain time, a reinforcing possitive loop involving a large number of RNA-subsystems could be established. The formation of such a hypercycle would give the involved RNA-systems an advantage over other RNA-systems with respect to their rate of production (a second order autocatalytic process), it would stabilize the total information carried by the cooperating RNA-systems, and it would permit the gradual development - hand in hand - of longer and longer RNA-molecules and of more and more specific proteins.

It is such formations of cooperative structures and the associated build-up of genetic codes that we have started to investigate by means of System Dynamics. Clearly, we are here dealing with a self-organizing process in the sense that more and more complex structures are generated. The process also involves characteristic spontaneous transitions starting as random mutations at the level of individual molecules and, if a positive feed-back is established, proceeding through amplifications over tens of decades until macroscopic numbers of mutants have been produced.

When several RNA-subsystems are considered, the number of possible couplings quickly becomes very large, and combinatory problems become significant. At the same time, DT-problems tend to arise when a system between periods of relatively slow development several times has to make transitions involving amplification from 1 to say 10^{30} molecules. For these reasons we have decided to model the self-organizing process in an approximative manner for which we have introduced the term "stochastic re-causalization".

In a stochastic re-causalization process it is assumed that all RNA-molecules of a given type mutate at one and the same time, i.e. the very rapid amplification processes are simulated by CLIP-functions which suddenly change the properties of a macroscopic number of molecules. In the flow-diagram this corresponds to random generation (and/or

disconnection) of causal links between RNA-subsystems. Each of these connections originate in the pool of proteins produced by one type of RNA-molecules and terminates in the replication rate of another type of RNA-molecules. Since amplification from molecular level only occurs when a hypercycle is established, only such combinations of causal links which give rise to closed loops are allowed.

The stochastic generation of causal links is complemented by functions that continuously evaluate the performance of the produced structures and stabilize reinforcing connections. This expresses the principle of natural selection which in the present context is a result of the competition between RNA-subsystems for resources.

It is relatively simple to give examples of re-causalization phenomena in social systems. One could think for instance of a company which "happened" to start a collaboration with a former competitor. Such a collaboration could imply division of markets or of product selections, or one company could start to produce semi-manufacture for the other. If this problem was extended to consider the establishment of mutually beneficial cooperative structures between several companies, it would resemble our RNA-problem a good deal.

Stochastic re-causalization and formation of RNA-hypercycles

At the present stage, our model of RNA-hypercycle formation operates with 3 RNA-subsystems, only. Figure 8 shows the flow-diagram for each of these subsystems. RNA-strands of type I=1,2,3 are synthesized from mono-nucleotides

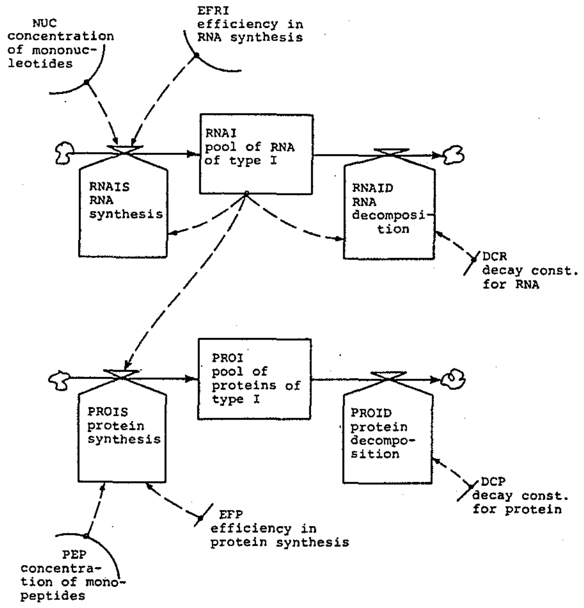


Figure 8. Flow-diagram for an RNA-subsystem. The model consists of three such sectors, a resource sector and a module that controls the stochastic intersector connections.

through base-pairing. The rate of this process RNAIS depends upon the amount of RNAI already formed, the concentration of nucleotides NUC and the efficiency of the replication process EFRI. This efficiency again depends upon possible catalyzing effects of simple proteins produced by other RNA-molecules. The produced RNA-molecules are subject to decomposition through hydrolysis and other processes, and the rate of decomposition RNAID is determined as the amount of RNAI multiplied by a characteristic decay constant DCR.

Proteins (poly-peptides) of type I are synthesized from mono-peptides (amino acids) by RNAI-molecules at a rate

which is determined by the amount of RNAI-molecules, the concentration of mono-peptides PEP, and the efficiency of protein synthesis EFP. Also proteins decompose, and the characteristic decay constant for this process is DCP.

Besides the three RNA-subsystems, the model also includes resource pools for mononucleotides and amino acids. We are considering an open system, and these resources are therefore continuously supplied. Finally, the model includes a set of equations that specify the random coupling and decoupling of RNA-subsystems. The re-causalizations are treated as Markov processes according to a formalism that we have previously described(13,14). Figure 9 gives an overview of some of the 21 possible hypercycles and combinations hereof which can exist with 3 RNA-subsystems.

Figures 10 and 11 give examples of the obtained simulation results. On each figure we have plotted the quantities of each of the three types of RNA. The states of the possible subsystem to subsystem connections are indicated through the values (1=connected, 0=disconnected) of the dummy variables plotted as A,B,C,D,E and F. From the variation of these dummies one can determine the development in the structure of the system. On figure 10 for instance, a hypercycle between subsystems 1 and 2 is established at about time 24. The amounts of RNA1 and RNA2 hereafter increase significantly, while the amount of RNA3 is reduced. Figure 11 shows how the formation of a hypercycle including all the RNA-subsystems can lead to sustained oscillations in the system. The occurrence of such limit cycles has previously been established by Eigen(19).

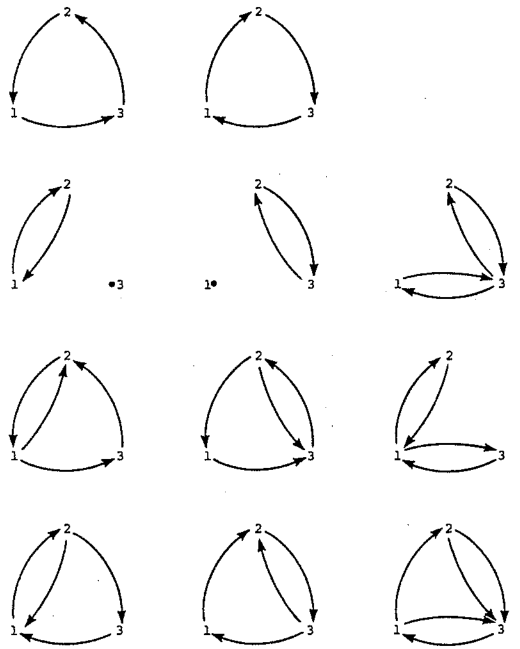


Figure 9. 11 out of the 21 possible hypercycles and combinations hereof which can exist in a model with 3 RNA-subsystems. In the case of four RNA-subsystems there can be about 500 different combinations of hypercycles, each with its characteristic mode of behaviour for the system as a whole.

It is characteristic for the re-causalization model that there is an uncertainty both with respect to which kind of hypercycle that happens to be established, and with respect to the time that this occurs.

Conclusion

We have discussed how instabilities in energetically open systems can lead to self-organizing processes. Such transitions exemplify the break down of the law of large numbers. Amplification of random noise plays a significant role, and the ave-

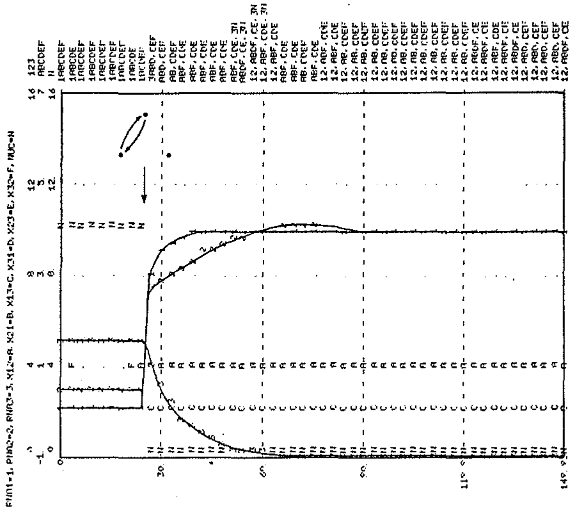


Figure 10. Simulation results obtained with the model of RNA hypercycle formation. In this run, a hypercycle involving RNA-subsystems 1 and 2 is generated at about time 24.

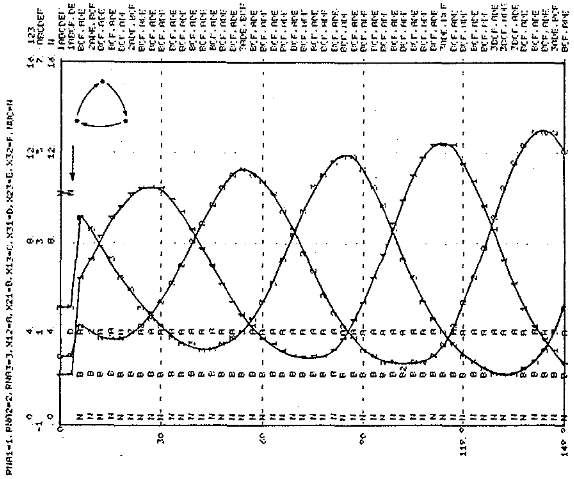


Figure 11. Same as figure 10 only with a different initiation of DYNAMO's noise function. A hypercycle involving all three RNA-subsystems is here generated, and the system starts to oscillate violently.

rage macroscopic variables are insufficient to determine system development. We have also shown how self-organizing transitions in social and biological systems can be modeled with System Dynamics. This requires methods capable of handling stochastic processes, but otherwise it does not imply expansions or generalizations of System Dynamics as a modeling technique.

Rather, it is the ideas that we have come to connect with System Dynamics about the stability of social systems which have to be complemented. We consider these ideas as a practical working hypothesis in many real life problems, and may be also as part of a tactical defence towards econometrics. They do not constitute an indisputable truth, however. According to the Brussels school, the evolution of social and biological systems can be considered as a series of unstable transitions interrupted by periods of more deterministic development. As we have tried to illustrate, this can be a very fruitful viewpoint, and we feel that it can be accomodated in System Dynamics without changing any of the more fundamental principles.

Self-organizing phenomena are not at all uncommon in natural sciences, and there is no reason to expect that the introduction of such processes in System Dynamics should weaken or undermine its basic ideas.

Appendix

Since the models are small and the DYNAMO equations at certain points a little unusual we have found it reasonable to list below the complete programs for the simple model of social revolution and for the model of self-organization in a mutating two-species system:

```
*   SIMPLE MODEL OF SOCIAL REVOLUTION (REVOL1)
NOTE
L   PIP.K=PIP.J-(DT)(NGLWE.JK+NGMPA.JK+NGRWE.JK)
N   PIP=PIPI
C   PIPI=2E7
L   LWE.K=LWE.J+(DT)(NGLWE.JK)
N   LWE=1.4E3
L   MPA.K=MPA.J+(DT)(NGMPA.JK)
N   MPA=3.6E3
L   RWE.K=RWE.J+(DT)(NGRWE.JK)
N   RWE=1.5E3
R   NGLWE.KL=((PIP.K/PIPI)*NALWE*(NOISE()+.5))-(LWE.K/ATLWE)
X   +(LWE.K*MGRLWE*MIST.K)(PIP.K/PIPI)
C   NALWE=0.8E3
C   ATLWE=2
C   MGRLWE=2.4
R   NGMPA.KL=((PIP.K/PIPI)*NAMPA*(NOISE()+.5))-(MPA.K/ATMPA)
X   +(MPA.K*MGRMPA*MIST.K)(PIP.K/PIPI)
C   NAMPA=2.4E3
C   ATMPA=3
C   MGRMPA=1.9
R   NGRWE.KL=((PIP.K/PIPI)*NARWE*(NOISE()+.5))-(RWE.K/ATRWE)
X   +(RWE.K*MGRRWE*MIST.K)(PIP.K/PIPI)
C   NARWE=0.6E3
C   ATRWE=1.9
C   MGRRWE=1.9
A   MIST.K=MAX(0,IST.K-THST)
C   THST=1
A   IST.K=TABLE(ISTT,TIME.K,0,60,20)
T   ISTT=0/2/2/2
SPEC   DT=.05/LENGTH=60/PLTPER=1
PLOT   IST=*/PIP=I,LWE=L,MPA=M,RWE=R(0,2E7)
RUN
```

```
*       SELF-ORGANIZATION IN A MUTATING TWO-SPECIES SYSTEM (MUTA1)
NOTE
L   RES.K=RES.J+(DT)(RIF.JK-ROF.JK-RUR.JK)
N   RES=RESI
C   RESI=6E4
R   RIF.KL=NRIF
C   NRIF=1E4
R   ROF.KL=RES.K/ARLT
C   ARLT=10
R   RUR.KL=MCA*NA.K+MCB*NB.K
C   MCA=1
C   MCB=1
A   SRA.K=RES.K/(NA.K+NB.K)
L   NA.K=NA.J+(DT)(NGRA.JK-MR.JK)
N   NA=(NRIF-(RESI/ARLT))/MCA
R   NGRA.KL=NA.K*MGRA*MRAA.K
C   MGRA=2.0
A   MRAA.K=TABLE(MRAAT,SRA.K,0,30,5)
T   MRAAT=-1/-.9/-.6/0/.6/.9/1
L   NB.K=NB.J+(DT)(NGRB.JK+MR.JK)
N   NB=0
R   NGRB.KL=NB.K*MGRB*MRAB.K
C   MGRB=2.0
A   MRAB.K=TABLE(MRABT,SRA.K+RAMB-(DREF.K*DREF.K),0,30,5)
T   MRABT=-1/-.9/-.6/0/.6/.9/1
C   RAMB=8.0
R   MR.KL=CLIP(0,1,NNAB.K,NMF*NA.K*DT)-CLIP(0,1,NNBA.K,NMF*NB.K*DT)
A   NNAB.K=NOISE()+.5
A   NNBA.K=NOISE()+.5
C   NMF=2E-5
L   REF.K=REF.J+(DT)(RFGR.JK-RFER.JK)
N   REF=0
R   RFGR.KL=NB.K*SRFG
C   SRFG=.8E-4
R   RFER.KL=REF.K/ARET
C   ARET=30
A   DREF.K=SMOOTH(REF.K,SMT)
C   SMT=10
SPEC   DT=.1/LENGTH=200/PLTPER=4
PLOT   NA=A,NB=B/RES=R/REF=W
RUN
NOISE  234567
RUN
NOISE  457683
RUN
NOISE  728465
RUN
```

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