COMMENTS ON THE CYBERNETICS OF STABILITY AND REGULATION IN SOCIAL SYSTEMS

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ABSTRACT

The methods and principles of cybernetics are applied to a discussion of stability and regulation in social systems taking a global viewpoint. The fundamental but still classical notion of stability as applied to homeostatic and ultrastable systems is discussed, with a particular reference to a specific well-studied example of a closed social group (the Tsembaga studied by Roy Rappaport in New Guinea).

The discussion extends to the problem of evolution in large systems and the question of regulating evolution is addressed without special qualifications. A more comprehensive idea of stability is introduced as the argument turns to the problem of evolution for viability in general.

Concepts pertaining to the problem of evolution are exemplified by a computer simulation model of an abstractly defined ecosystem in which various dynamic processes occur allowing the study of adaptive and evolutionary behavior. In particular, the role of coalition formation and cooperative behavior is stressed as a key factor in the evolution of complexity.

The model consists of a population of several species of dimensionless automata inhabiting a geometrically defined environment in which a commodity essential for metabolic requirements (food) appears. Automata can sense properties of their environment, move about it, compete for food, repro-

duce or combine into coalitions thus forming new and more complex species. Each species is associated with a specific genotype from which the species' behavioral characteristics (its phenotype) are derived. Complexity and survival efficiency of species increases through coalition formation, an event which occurs when automata are faced with an "undecidable" situation that is resolvable only by forming a new and more complex organization.

Exogenous manipulation of the food distribution pattern and other critical factors produces different environmental conditions resulting in different behavior patterns of automata and in different evolutionary "pathways."

Eve-1, the computer program developed to implement this model, accepts a high-level command language which allows for the setting of parameters, definition of initial configurations, and control of output formats. Results of the simulation are produced graphically and include various pertinent tables. The program was given a modular hierarchical structure which allows easy generation of new versions incorporating different sets of rules.

The model strives to capture the essence of the evolution of complexity viewed as a general process rather than to describe the evolution of a particular "real" system. In this respect it is not context-specific, and the behaviors which are observable in different runs can receive various interpretation depending on specific identifications. Of these, biological, ecological, and sociological interpretations are the most obvious and the latter, in particular, is stressed.

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INTRODUCTION

Many valuable investigations and practical enterprises have brought the methods and principles of cybernetics to bear upon the regulation of large systems; societies, firms and other business organizations, command and control systems, some special and relatively tractable cases of closed social groups studied by anthropologists (for example, the Tsembaga, discussed as an outstandingly clear study in section 1.2) and more. In general, the classical notion of "stability" has been employed, i.e., the maintenance of dynamic or static equilibrium, wholly or partly invariant with "goal" conditions that are specified within the framework of sensibly chosen but predetermined state variables.

This approach, though indubitably correct as far as it goes, runs into difficulties when the system is evolutionary; a point which is readily exemplified by considering the other than closed aspects of the Tsembaga society, i.e. the reassignment of people to local groups who perform the ritual and thus maintain ecological stability as well as social identity. One manifestation of the difficulties is as follows: although the principles of cybernetics are piecemeal applicable, it is difficult to apply the cybernetic paradigms which have burgeoned since the early 1970's to provide, as they can, a unifying theory and its proper interpretations.

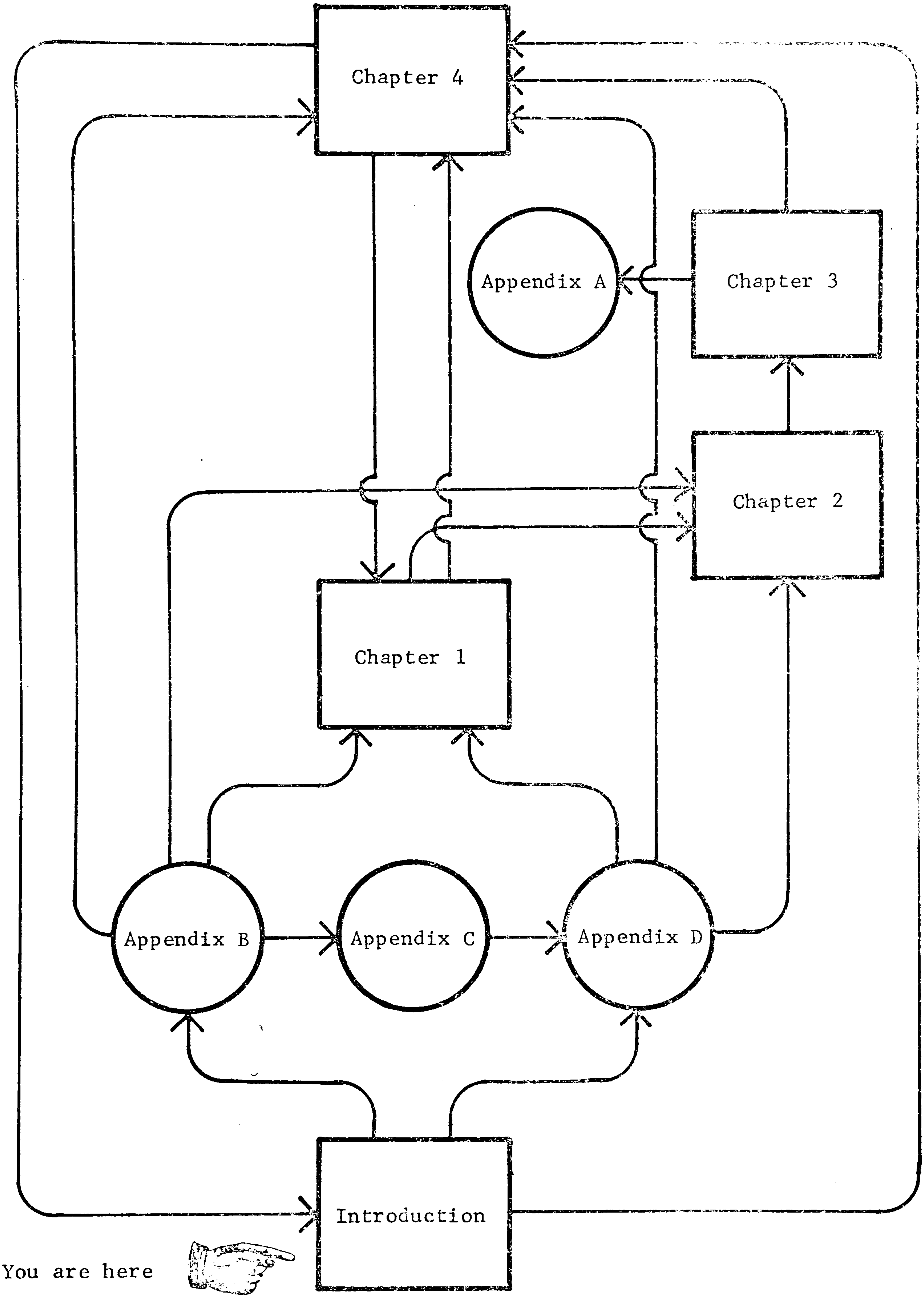
In this thesis I try to extend the cybernetics of large social systems in order to obtain a greater degree of unification and show, by considering special simulation and modelling programs (Chapter 3 which contains the burden of the argument) that essays of this kind are implementable. The other chapters of the thesis are concerned with the requisite background and an outline of an interpretation of the implemented calculus related to historical data the details of which are presented in Appendix C and Appendix D of the work.

The thesis contents are thus arranged in the following manner. (See also the diagrammatic representation below.) Chapter 1 describes the fundamental but still classical notion of stability as applied to homeostatic and ultrastable systems giving general examples in section 1.1 and a specific, well-studied example (the Tsembaga ritual cycle) which is discussed and reanalyzed in section 1.2. Much of the historical acknowledgment together with detailed exemplification is relegated to Appendix B. Chapter 2 addresses the problem of evolution (with biological, social, ecological and other large systems in mind); the question of "regulating" evolution is discussed without special qualifications in section 2.1, and the more comprehensive idea of stability as "organizational closure" (self-reconstruction and P Individuation are nearly equisignificant) is introduced in section 2.2 where the argument turns to evolution for viability, survival and development; growth in structural sophistication and/or distribution of control being prerequisites for correct establishment of "viability."

Chapter 3, by far the more lengthy, is devoted to a simulation model Eve-1, intended to exemplify my thesis and also to provide the basis for a variety of practical, predictive and regulatory tools. The behavior and characteristics of the Eve-1 computer program are described globally in this chapter since the detailed construction, listing and data organization of Eve-1 are dealt with in Appendix A. (However, typical runs are discussed and given an interpretation in Chapter 3.) It should be stressed that Eve-1, or any other computer program of its kind, is a simulation and not a realization; not, that is, an actual doing. The point is important because concepts like "organizational closure" or "evolution" refer to realizations. The simulating program acts as a guide and highlights imperfections of any simulation, a fact which became obtrusive as the Eve-1 program was designed. But it is equally important to notice that a realization, in the genuine sense, is possible and requires only a slight departure from the available technology. Chapter 4 includes an interpretative discussion, addressed particularly to a view of society and of the dynamics of stability in social systems, together with conclusions and some speculative comments.

An important application of the work (others are implicit in the argument even if not explicitly spelled out in the body of the thesis) concerns problems of social development in their broadest sense. One conclusion, appropriate in that context, is that "sane" social development (evolution) and decentralized/distributed/control are not as often supposed incompatible but simply different facets of the same innate mutualism which promotes evolution and is the more recently advanced, peculiarly cybernetic concept of stability.

The material delegated to Appendices B, C and D contains a review of cybernetics and system theoretic concepts which are pertinent to the content of chapters 1, 2, 3 and 4. This background material could be helpful to a reader who is not familiar with the now classical concepts of cybernetics. Otherwise, Chapter 1 is the logical place to begin and brief reference to the appendices can be made according to indications in the text. Notes to Chapters 1, 2, 3 and 4 appear immediately after Chapter 4 whereas notes related to Appendices B, C and D follow each appendix respectively.



A Schematic Representation of the Contents

1. HOMEOSTASIS AND STEADY STATE REGULATION IN A WELL ADAPTED SOCIETY

1-1. Homeostatic Regulation

1-1.1. Stability and Homeostasis

The concept of homeostasis is crucial to the understanding of processes that maintain equilibrium in viable systems. It provides a unifying principle underlying those activities which mediate the stability of viable organizations under certain conditions of displacement from established norms.

The term "stability," when it is used in relation to dynamic systems, implies that some fundamental condition remains invariant in spite of changes that a system may be undergoing. Such an invariance--the state that is not changed by the system's transformations--represents the state of equilibrium for that system, and this state of equilibrium will be more or less stable, depending on how sensitive it is to disturbances acting to displace it.

In viable systems of even a relatively moderate complexity, equilibrium is rarely associated with a single state. Instead, it is defined by a set of states, and systems of this kind will be stable, as long as disturbances do not lead to a permanent displacement from states that belong to that set.(1) An important feature of systems that are characterized by multiple states of equilibrium is that their stability is a composite property of the whole. It presupposes that the system's interacting components are stable and it depends on some degree of coordination between the activities of these components.(2)

Depending on the type of system that is under consideration, conditions of equilibrium may assume substantially different forms. Von Foerster, for example, has emphasized this point in discussing the different types of equilibrium that are associated with mechanical, thermodynamic and homeostatic systems respectively.(3) In the case of mechanical systems, Von Foerster has pointed out, the notion of equilibrium is associated with motion. Specifically, "with that motion--among all possible motions--for which a certain mechanical quantity--action--is minimized." In thermodynamic systems, where behavior is described in statistical terms because of a fundamental uncertainty about the system's microscopic states, equilibrium is associated with "the set of all states for which a certain probabilistic quantity--entropy--is maximized." Finally, in the case of homeostatic systems, "equilibrium is obtained by an organized structure which channels available energy in such a way that it opposes deviations from a certain state of the system."(4)

The term "homeostasis" was originally coined by Cannon(5) in order to describe the condition of dynamic equilibrium by virtue of which organisms maintain their integrity in spite of impinging environmental disturbances. Living organisms are vulnerable, healthy life being able to thrive only within a narrow range of conditions. A living organism is an open system (see Appendix C, section C-5) engaged in a continuous exchange of materials with its external world. Entropic processes act to dissolve the orderly coherence characterizing a functioning organism and make it uniform with its surrounding. These processes are countered by an opposing activity by which environmental constituents are being continuously synthesized into a stable pattern, and by which the integrity of the organism is, at least temporarily, maintained.

The idea that living organisms are stable entities maintaining a fragile integrity in the face of constant environmental flux was not altogether new to 20th Century biologists. In its primitive form, Cannon traced the concept to Hippocrates. It is only in the 19th Century, however, that earlier "vitalistic" notions gave way to essentially physiological explanations anticipating the key cybernetic ideas of feedback and control. In 1817, Magendie used the term "reflexis" to define the cyclical activity produced by a disturbance which traveled along specific channels from the affected part of the body to the central nervous system, to be reflected along other channels back to the point of origin, where it reversed or inhibited the effects of the disturbance which initiated it.(6) Later (1878), Claude Bernard suggested that in order to survive perturbations originating from the external world, an organism must be able to maintain an internal environment, its "milieu interne," in a constant condition. He wrote: "It is the fixity of the 'milieu interieur' which is the condition of free and independent life, and all the vital mechanisms, however varied they may be, have only one object, that of preserving the internal environment."(7)

Following these ideas Cannon was able to demonstrate that the stability of the animal's internal environment is mediated by complex interactions of specific physiological process. He defined homeostasis as the steady states maintained in the organism by the coordinated activity of its interacting physiological processes.(8) These, he showed, were organized in a cyclic chain of cause and effect whereby a displacement from a normal condition set in motion compensating actions reversing the effects of the displacement.

While the idea of reflexis was conceived in relation to the organism's automatic "behavioral" reactions to external disturbances, homeostasis has been associated with processes that maintain its internal environment stable. Cybernetics has shown both mechanisms to be essentially of a similar type. In both, an established condition constituting a "norm," is maintained by complex cyclic chains of activities. Both are goal-directed and self-regulating (in the sense of Appendix C, section C-7) and belong to the general class of purposeful mechanisms whose universal operating structure was brought to light by Bigelow, Wiener and Rosenblueth.

Homeostatic mechanisms operate as error-controlled regulators following the scheme of a typical feedback system. The structure of the mechanism entails the following functional elements: a goal setting device defining the desired state of the system; an arrangement by which the actual condition of the system can be monitored; a means for comparing the actual with the desired state and computing the discrepancy between the two; and finally a mechanism which is activated to correct for deviations when a discrepancy between the actual and the desired state of the system is registered.

These basic functions are organized in a closed loop structure that is characteristic of a feedback system. In the case of homeostatic mechanisms, the feedback around the circuit is negative. (For the generalized block-diagram, see Figure C-3 of section C-7 in Appendix C.) The mechanism operates as follows: an input signal representing the goal, and a signal representing the actual state of the system are fed into a comparator where the value of the latter is subtracted from the former to obtain a measure of deviation. From this measure of deviation a control signal is derived. It is used to activate the appropriate "effector" which acts to reduce the detected error and restore the system to its desired state. There is a constant monitoring of the system's actual condition and measures of discrepancy are continuously fed back around the closed circuit with the result of keeping the system stable around its assigned equilibrium.

In technological devices such as a man-made servomechanism, elements represented in the typical feedback loop diagram, and the information channels which connect them, normally coincide with specific and functionally distinct pieces of hardware. In biological systems, on the other hand, where physiological processes involving chemical reactions are concerned, complexity may rule out the possibility of resolving the functioning of the whole mechanisms into distinct entities.(9) The general principle of self-regulation underlies both, and it is universally applicable to all the physiological processes which operate to maintain vital conditions constant.

A typical case is that of temperature regulation in warm-blooded animals.(10) A drop in the temperature of the body stimulates the appropriate centers in the nervous system and these activate various heat-producing mechanisms as well as processes which act to reduce heat losses. The actual body temperature is monitored back to the controlling center (which is located in the diencephalon in the base of the brain) either by the temperature of the blood or by nerve impulses arriving from the surface of the body. By means of such continuous monitoring and the activation of appropriate mechanisms that oppose deviations from the norm, the temperature of the body's internal environment is kept uniform.

Similar homeostatic mechanisms regulate the constancy of a great number of other physiological conditions. In addition to thermoregulation, they involve the regulation of osmotic pressure and body posture, the regulation of salt concentration in the blood, of blood sugar, blood protein, blood fat and calcium, the regulation of adequate oxygen supply and respiration in general, the regulation of the coagulation of blood, blood clotting and many more. Notwithstanding their specific mode of functioning,(11) the basic operational features of these varied mechanisms are similar. They all operate promptly and automatically to reverse the effects of adverse conditions that threaten internal stability.

The automatic operation of homeostatic mechanisms is essential in guaranteeing a high likelihood of success in maintaining critical conditions constant. These mechanisms have been perfected by countless generations and by a long evolutionary experience. They operate by following precise procedures, built into the organism by a long adaptive interaction with a particular environment, and by the survival optimizing experiences that such an interaction entails. There seems to be a principle involved, which turns a problem threatening survival, once it is effectively "solved," into a prescription for action that can be followed routinely and automatically. This automatic functioning of physiological homeostatic mechanisms is particularly significant to higher animals, as it makes possible the investment of "creative" energies in higher forms of behavior. As Cannon suggested: "We find the organism liberated for its more complicated and socially important tasks because it lives in a fluid matrix which is automatically kept in a constant condition."(12)

While the underlying principles are similar, the simplicity implied in a negative feedback system with a single loop rarely coincides with the structure of homeostatic mechanisms in the body. Homeostatic mechanism in biological organisms are embodied in a complex web-like structure of interacting processes, such that unique partitioning is often quite impossible. Thus, different physiological processes may interact to maintain a single equilibrium, or the very same processes may be involved with the functioning of a few different homeostatic systems. The point has been stressed by Goldman,(13) who demonstrated the great redundancy associated with mechanisms regulating blood sugar. Such a use of redundancy is typical to physiological processes and to biological organisms in general.(14) It ensures a reduction in operational errors and offers a considerable factor of safety against possible malfunctioning of vital mechanisms. It is precisely this redundance in mechanisms that ensures adaptive capabilities and guarantees the flexible viability and enormous stability of biological organisms.

1-1.2. Homeostasis and Ultrastability

Cannon's original concept of homeostasis has been extended significantly by Ashby who developed a rigorous formulation,(15) linking the idea of homeostasis to the general problems of adaptation and survival. The key idea in Ashby's formulation is that the concept of a system's survival can be objectively defined with respect to a set of critical variables-- its "essential" variables--the nature and value of which will vary for different systems. In biological organisms, for example, essential variables are physiological in nature. They are fixed (genetically) and species specific. For an animal to survive requires keeping the value of its essential variables within specific physiological limits. This end is mediated by homeostatic mechanisms which maintain the stability of essential variables in spite of impinging disturbances.

Homeostasis is achieved when regulation is exercised such that the effect of a disturbance is so matched to the actions of a regulating mechanism that the outcome of their interaction restores the value of an essential variable even after a displacement. Such regulation is affected by physiological processes (such as those brought to light by Cannon) but higher manifestations of behavior operate to ensure the same end. The principles of homeostasis which underlie both are identical.(16)

A system's homeostasis is a manifestation of its adaptation to a specific environment in the sense that homeostatic mechanisms relate to specific disturbances which are typical features of a given environment. If such an environment is orderly, if it is subject to the operation of a set of unvarying constraints, some "disturbances" will occur, and reoccur, with a higher probability than others. The homeostatic mechanisms that are actually operative in a system reflect a measure of this probability. They are set up to coincide with the typical pattern of events dominating the system's interaction with its world.

The same idea can be stated differently by saying that the transfer function which determines a system's counter-disturbance action, its "behavioral" output, must bear some specific relation to inputs originating from its surroundings. If we assume varying input signals representing different external conditions, we would say that a system has adapted to its environment if its activities coincide with a particular distribution of signals characterizing conditions in the environment, such that an overall stability is maintained.

Ashby's thesis is that "adaptive" behavior corresponds to a behavior which maintains essential variables within their physiological limits.(17) The idea of adaptation is thus linked to the notion of a behavior of a stable system, "the region of the stability being the region of the phase-space in which all the essential variables lie within their normal limits."(18) Seen in this perspective, the concept of homeostasis can be extended from the animal's inborn, internal processes to the wide range of activities it directs towards the world, and it is equally applicable to the simple activities of lower organisms and to the more complex behavior of higher animals. All these have one common goal: promoting survival.

Here, a problem is encountered. In simple servomechanisms, as in the vegetative system of biological organisms, homeostatic mechanisms respond correctly because critical disturbances have been anticipated and the appropriate responses have been prescribed in advance. (By the designer in the case of a servomechanisms, and by the long experience of interacting with a specific environment in the case of an organism.) Such simple homeostatic mechanisms, in which actions restoring stability are wholly prespecified, cannot account for the general problem of adaptive behavior. The original concept of homeostasis had to be extended, therefore, in order to explain a capability of preserving stability even in the face of unpredictable perturbations. This extension is provided by the concept of ultrastability.

An ultrastable system is capable of restoring a stable state even under conditions where remedial actions are not fully specified by its transfer function. This capability involves an alteration of the transfer function itself, in a way that adjusts it to varying disturbances. There clearly is a limit to the magnitude of displacement that a given system can tolerate. The essence of the idea of adaptation, however, is that within an acceptable range of perturbations an adaptive system can maintain stability even if it is confronted with a new and "unfamiliar" disturbance. Effects of such a disturbance can be reversed if the value of an existing transfer function is altered, continuously or by a step function, until a configuration is hit upon under which stability is restored. A process of trial and error is implied which underlies the search for an appropriate transformation. As Ashby argues, "The basic rule for adaptation by trial and error is: --if the trial is unsuccessful, change the way of behaving; when and only when it is successful, retain the way of behaving."(19)

In the ultrastable system, Beer points out, there is no need to predict disturbances or even to understand their origin. "To be aware of something happening and label it disturbances, and to be able to alter internal states until the effects of the disturbance are offset, is enough."(20) The difference is in the strategy employed by a simple automatic controller on the one hand, and an adaptive controller on the other.(21) In the former, there is a specific decision rule available which specifies explicitly what corrective action is to be taken for each defineable change of state in the environment. In the latter, unpredictable disturbances are admitted and there is no unique decision rule for the system to follow. Instead, there is a general strategy (underspecified in the sense of section C-8 in Appendix C) directing the system to "experiment" with a set of possible state transformations in a search which, following a displacement, is to be continued until a former state of stability is restored, or a new state of stability found.

Adaptation by ultrastability, according to Ashby, can be explained by assuming a mechanism of "self-vetoing" which excludes all partial states of equilibrium accepting only those states for which all the system's essential variables are within their normal limits.(22) This is to say that for a dynamic system with multiple equilibria to be stable, all its interacting parts must each be in a state of equilibrium. If we imagine two parts, A and B, coupled to each other such that the output of one is the input of the other and vice-versa, the system as a whole can reach a state of equilibrium only if both A and B are in an equilibrial condition. If only one part settles into a state of equilibrium, the instability of the other will force it out and the process will continue until a condition of stability is found which includes both. There is a process of selection involved acting towards the condition of equilibrium which satisfies the whole. It accounts for the dynamic stability that is typical to adaptive processes, lending the concept of ultrastability its great generality.

1-1.3. The Universality of Homeostatic Mechanisms

The concept of homeostasis articulates the principle of a particular type of stability where deviations from a system's states of equilibrium are opposed by the appropriate, self-induced, counter actions. The concept is embodied in mechanisms which are characterized by a specific structure and it is associated with processes involving goal directedness and self-regulation. The operation of homeostatic mechanisms has been identified with the working of the internal vegetative system in biological organisms and it has been extended to account for various higher manifestations of behavior as well. The principle extends even further as it is manifest in a great variety of systems in all levels of reality. Consequently, while the concept originated in physiology, it is now used quite universally to describe a principle of regulation and a condition of stability that are typical under certain circumstances to dynamic systems in general.

The ideas of homeostasis and error-controlled regulation in physiology and man-made servomechanisms have provided an important source to early developments in cybernetics, and, in this context, they have been discussed extensively.(23) These concepts have subsequently been found useful in accounting for the characteristics of regulatory processes in significantly diverse phenomena. A few cases, selected from different fields ranging from genetics to ecology, will illustrate the point.

Lerner, for example, has suggested that homeostatic mechanisms can be identified on the genetic level of an interbreeding population. In such a population, he has shown, there is a tendency to equilibrate the genetic compositon and there are self-regulating processes at work which resist sudden changes from established genetic equilibrium.(24) Similarly, Jung has described the psyche in terms of self-regulating processes which operate to maintain a state of equilibrium and which are characterized by compensating actions that follow stressful events.(25)

On the level of social systems, the concept of homeostasis has found an extensive use and the working of homeostatic mechanisms in society have been linked to the function of established traditions, social conventions, rituals and the like. Cannon himself emphasized the significance of viewing various social processes with the notion of homeostatic stability in mind and in the epilogue to The Wisdom of the Body he suggested the existence of an analogy between physiological and social homeostasis. Wiener discussed the stability in small and "closely knit" communities in similar terms,(26) and since the advent of the Macy Conferences immediately following the Second World War, the notion of steady state regulation in social systems has become an important tool in the conceptual kit of anthropologists.(27) Specifically, there are models like Wilkins', for example, who proposed that the distribution of certain attributes in a population, such as different occupations, are characterized by statistical regularities which are maintained by various social pressures acting to keep an established status-quo.(28) A different kind of model portraying social homeostasis is offered by Rappaport,(29) in a study which emphasizes the regulatory function of rituals in maintaining a society stable in the context of its environment. In the more specialized area of management science, Beer has provided models of homeostatic regulation in industry and business organizations.(30)

On yet another level, that of ecological systems, it is now recognized that there are many complex homeostatic mechanisms at work. Wynne Edwards, for example, discussed the role of communication-related processes in maintaining population densities of animals stable, and he emphasized the symbolic function of display behavior in mediating this stability.(31) Slobodkin performed a series of convincing laboratory experiments showing the tendency of an ecosystem consisting of various animals and plants to settle into a condition of steady state. When perturbations are introduced into such stable environments, various compensating mechanisms are brought into play involving changes in reproduction rate, body size, development rate, and so forth.(32)

These are only few and brief examples, but they serve to illustrate a crucial point, namely that from the viewpoint of regulation there is clearly a general principle at work cutting across the levels into which reality is conceptually demarcated, and integrating its dynamic manifestations in a complex heterarchy of mutually interacting and interaccommodating self-regulating processes.

In the following pages attention will be focused on an example of steady state regulation in a social system. This from a particular viewpoint that seeks to emphasize the global characteristics of homeostatic regulation in a well-adapted society viewed as a whole. Rappaport's work on the Tsembaga, a New Guinea people, has brought to light the regulatory function of rituals in mediating the homeostatic stability of a specific society in the context of its ecology. It is a particularly suitable illustration, and it will be discussed extensively below.

1-2. Steady State Regulation in a Well-Adapted Social System

1-2.1. The Tsembaga--General Background

In Pigs for the Ancestors,(33) Rappaport provides an anthropological account of the Tsembaga, a small and closely bounded cluster of clans who inhabit a remote and physically isolated territory within the "Bismarck Mountains" range of New Guinea. At the time when Rappaport's fieldwork was carried out (October 1962 to December 1963), the Tsembaga had still been only minimally exposed to Europeans. They could thus offer a case study of an isolated local culture adapted to the specific circumstances of its particular environment. A major concern of Rappaport's study is with an interpretation of the function of religious behavior, specifically the function of rituals shared by the Tsembaga, in affecting the fundamental relationships between major components comprising their local system.

The study emphasizes the role of rituals in the context of the adaptation of a social system to specific environmental circumstances. It brings to light not only the function of rituals in mediating the relationships between members of a closely knit community, but also the ways in which rituals regulate relationships between such a community and pertinent entities in its environment. Rituals, in other words, are shown to have an important practical effect on the external world, namely, the environment in which the social system exists and of which it is an integral part. The regulating function of rituals is interpreted in essentially cybernetic terms, thus making the study especially useful in illustrating the kind of stability which is typical to well adapted societies existing in environments that are characterized by a low rate of change.

Before we move to discuss the functioning of ritual as a mechanism of regulation, a few brief notes on the Tsembaga and their background may be appropriate. (34) The Tsembaga consists of a group which includes approximately 200 individuals occupying an area of roughly three square miles. They are one of about 20 similar local groups that range in size from 100 to 900 individuals, comprising a total population of roughly 7000 people sharing a common language (Maring) and living in a close proximity within the adjacent "Jimi" and "Simbai" valleys. The terrain of the region they inhabit is mountainous and heavily forested, and within the small territory occupied by the Tsembaga altitudes range from 2,200 to 7,200 feet, with slopes becoming pronouncedly steep above 5,000 feet. Measured orthographically, Tsembaga territory includes some 2,033 acres, almost half (48%) of which are covered by virgin forest or growth resembling virgin forest. Computed by the total orthographic area, population density is about 64 persons per square mile.

The local technology is extremely simple including such tools as digging sticks, steel axes and bushknives that are used for gardening. Bows and arrows are used for hunting as well as for warfare, where they are supplemented with spears, axes, and wooden shields. Various simple traps are also used and gourds as well as bamboo tubes are utilized as containers and cooking vessels, although most cooking is done on open fires or in earth ovens. Various local fibres are employed for weaving such items as loin cloths, net bags, caps, strings, aprons, and so forth. Prior to exposure to the Australians who now administer their territory, the Tsembaga used to manufacture salt (by boiling mineral water), some of which was traded for stone ax blades produced by a neighboring group.

Tsembaga subsistence depends on horticulture, silviculture, hunting, gathering, and the domestication of animals. Gardens are cut in the forest and they are planted with taro, yam, sweet potatoes, and sugar cane. Manioc, bananas, other fruits and various greens are also included. Various trees bearing edible materials are planted, some in groves, providing the population with edible green leaves and fruits. Hunting, trapping, and gathering contribute a large variety of non-domesticated resources, ranging from wild animals and additional vegetables to fire wood, building materials, and other essential substances. Animal husbandry includes pigs, dogs, chickens, and cassowaries, but pigs are by far the most important.

In addition to providing the Tsembaga with a source of nutrients, pigs assist in the cultivation of gardens where, by digging for roots, they eliminate weeds and seedling trees, turning and softening the ground thus making future planting easier. Pigs also help keep residential areas clean by feeding on garbage and human feces, and they provide an easily accessible source of protein when protein is needed at times of stress or physical injury. Tsembaga ritual is closely bound up with pigs. Various rituals require sacrificial slaughter of pigs and the length of the ritual cycle itself, as well as the occurrence of specific events that mark it, depend on the size and composition of the pig herd. Pigs, especially young ones, are cared for with a great deal of attention, sharing living quarters with women until they are about one year old. During this time pigs are subjected to a great deal of petting and stroking and are provided with choice food, thus becoming strongly bound to humans. The bond that is established is so strong that, as Rappaport points out, "it is hardly facetious to say that the pig through its early socialization becomes a member of a Maring family."(35)

Like other similar local groups, the Tsembaga form a single territorial unit as far as defense and the sharing of local resources are concerned. Within the boundaries of their territory, all Tsembaga share the rights to non-domesticated resources. These rights are exclusive to the Tsembaga in that they exclude all other local groups which are associated, in turn, with their own exclusive areas. It is within their well-defined, jointly defended and shared territory that the Tsembaga form a coherent population in a social as well as ecological sense. Inside this shared territory there is a division into smaller sub-territories associated with memberships in clans and sub-clans. Within these, particular garden sites are claimed by individual males. Title to the land is normally associated with patrilineal inheritance or the clearance of a new site. It is not very rigidly established, however, and men who lack sufficient land for cultivation may obtain it simply by approaching a better endowed member of their sub-clan and asking for a transfer of ownership. Similar transfers may also occur between whole sub-clans, with the result that inequities do not tend to reinforce themselves.

Inside Tsembaga territory, residential patterns do not follow land use, and they change significantly during the ritual cycle. A residential pattern may be highly nucleated at one point in the cycle, but as the pig herd grows a more scattered pattern becomes typical. The structure and nature of social relationships depend, to a great extent, on the residential pattern and how the latter fluctuates with varying densities. Social relations and intermingling intensifies as density rises until a point of intolerable density is reached where fusion occurs, decreasing thereby the intensity of social contacts. As a rule, men and women live in separate quarters. Men share communal houses, whereas married women and widows have each a separate house in which they live with unmarried daughters, young sons, and pigs.

Among the Tsembaga there are no designated chieftains or privileged individuals who hold substantial authority over others. While some men are especially admired for their experience, capabilities, or "knowledge," decisions are reached communally and are not generated repeatedly by a specific powerful individual. Decisions are reached during seemingly unstructured discussions and they tend to reflect a spontaneous concensus formed during the general "airing" of opinions. Following such discussions, specific decisions are not actually formulated, but any individual may initiate an act that is pertinent to the problem under discussion. If the general concensus is in agreement with his initiatory action, he will be joined eventually by others. Otherwise, the action will not be pursued.

Relationships with other local groups are either friendly or hostile. If relations are friendly, they are manifest in the exchange of women, goods, and pork, and in alliances during warfare. If relations are hostile, they are characterized by rigidly self-enforced "mutual avoidance" and by occasional outbreaks of actual warfare. Because of the stiff requirements to avenge all casualties that bind both sides, and because an even score is difficult to achieve, local wars tend to perpetuate themselves. Nevertheless, a truce may put a temporary end to fighting even if the score remains uneven. Like all other important features of Tsembaga life, both friendly and hostile relations are regulated by the performance of specific rituals. The ritual dominates the behavior of the entire system, integrating its various components and mediating the stability of particular variables as well as the viability of the system as a whole.

1-2.2. The Ritual Cycle

Rituals performed by the Tsembaga in the context of their ritual cycle affect entities which, together with the Tsembaga themselves, constitute the entire local ecosystem. The major components of this local ecosystem interact in many complex ways and they affect one another continuously. The crucial issue in Rappaport's study centers around his interpretation of the role of rituals in mediating the relations between entities that interact to form the entire system.

These entities include the Tsembaga population, other living organisms, especially pigs, the local vegetation, the non-living components of the environment and, in a sense, the spirits which constitute for the Tsembaga a "real" part of the world. In the context of a larger and more inclusive regional system, other neighboring human groups are also included.(36) Specifically, as Rappaport points out, the performance of rituals affects the following:

*The relationships between humans, pigs, and gardens.

*The killing of pigs and the distribution and consumption of pork.

*The hunting and consumption of non-domesticated animals.

*The density of human population and the distribution of land.

*The frequency and severity of warfare.

*The exchange of goods and people between local groups.

The ritual cycle functions as a regulating mechanism, operating to maintain pertinent system's variables within desired limits. "Essential" variables in the sense of Ashby are here associated with such quantities as the size of the local human population, the amount of land under cultivation, the number of pigs, and others. To an outside observer (such as the anthropologist), the system as a whole appears as self-regulating in that any "internal" deviation from a desired norm initiates automatically a process that restores stability. The initiation of an appropriate stabilizing process is regulated entirely by the ritual cycle, and the nature of each such process relates to the performance of a specific ritual.

The Tsembaga ritual cycle is characterized by the performance of rituals in a prescribed routine consisting of related events that follow each other sequentially. The cycle is marked by four major events which are associated with the performance of specific rituals and which signal significant transition points of the whole system. According to Rappaport the cycle may take twelve to fifteen years to complete (significant departures from this mean are possible), depending on the conditions of the pig population and other relevant factors. Events which occur during the cycle are contingent upon states of various components in the regional system and the rituals that are performed during the cycle affect the value of these components and the relations between them. For example, the completion of the "Kaiko," the year-long festival during which the size of the pig herd is drastically reduced, signals the beginning of a period in which warfare between local groups may be initiated. On the other hand, performance of the ritual in which "rumbim," a local plant, is planted ceremonially, terminates the period of warfare and signals a strict prohibition on the initiation of open hostilities. This prohibition lasts until the state of the whole system "requires" that the Kaiko will be staged once more, to be followed by the eruption of fightings, and so the cycle repeats itself.

Rituals that are performed in conjunction with the four major events in the cycle rarely relate to a single state of the system. They effect the whole system in different and complex ways. Thus, the Kaiko which serves to reduce the number of pigs when the herd reaches an intolerable size, also affects regional distribution of goods, the stimulation of matings between members of friendly local groups, and the encouragement of various other manifestations of social interaction and social exchange. Similarly, the planting of rumbim, which signifies the termination of fighting, serves to redefine the association of individuals with particular local groups as well.

To illustrate the nature of the processes involved, some of the major features of the ritual cycle as well as the dynamics of the mechanisms that regulate the size of the pig population, local trade, the distribution of wealth and the exchange of people between local groups, are summarized in

Figures 1 to 6 below.

Figure 1 provides a simplified representation of the structure of the ritual cycle showing the sequence of major events that dominate it. A somewhat more detailed representation is given in Figure 2, where the major events of the cycle are depicted as transition points for the whole system (circles), and the characteristics of the periods that follow each such transition are described (rectangular boxes). The most prominent feature of the cycle, as illustrated by Figures 1 and 2, is the regulation of alternating periods of peace and fighting, and of a time in which the pig herd is allowed to grow in size and a time in which it is deliberately reduced.

The cycle, according to Rappaport's account, culminates with the "Kaiko," a year-long festival marked by an extensive slaughter of pigs. The Kaiko is initiated by a ritual in which the rumbim, planted ceremonially after previous termination of fighting, is uprooted. The signal that the time has come to uproot the rumbim, and consequently to initiate the Kaiko, is provided by rising social tension, and especially by increasing women's discontent expressed in extensive wailing. This discontent results from an increase in the number of pigs which puts a growing pressure on the women who have to tend them. Actual preparations for the Kaiko begin with a ritual in which stakes are planted at the territory's boundary. This ritual, in which members of other friendly local groups participate, acts to redefine territorial

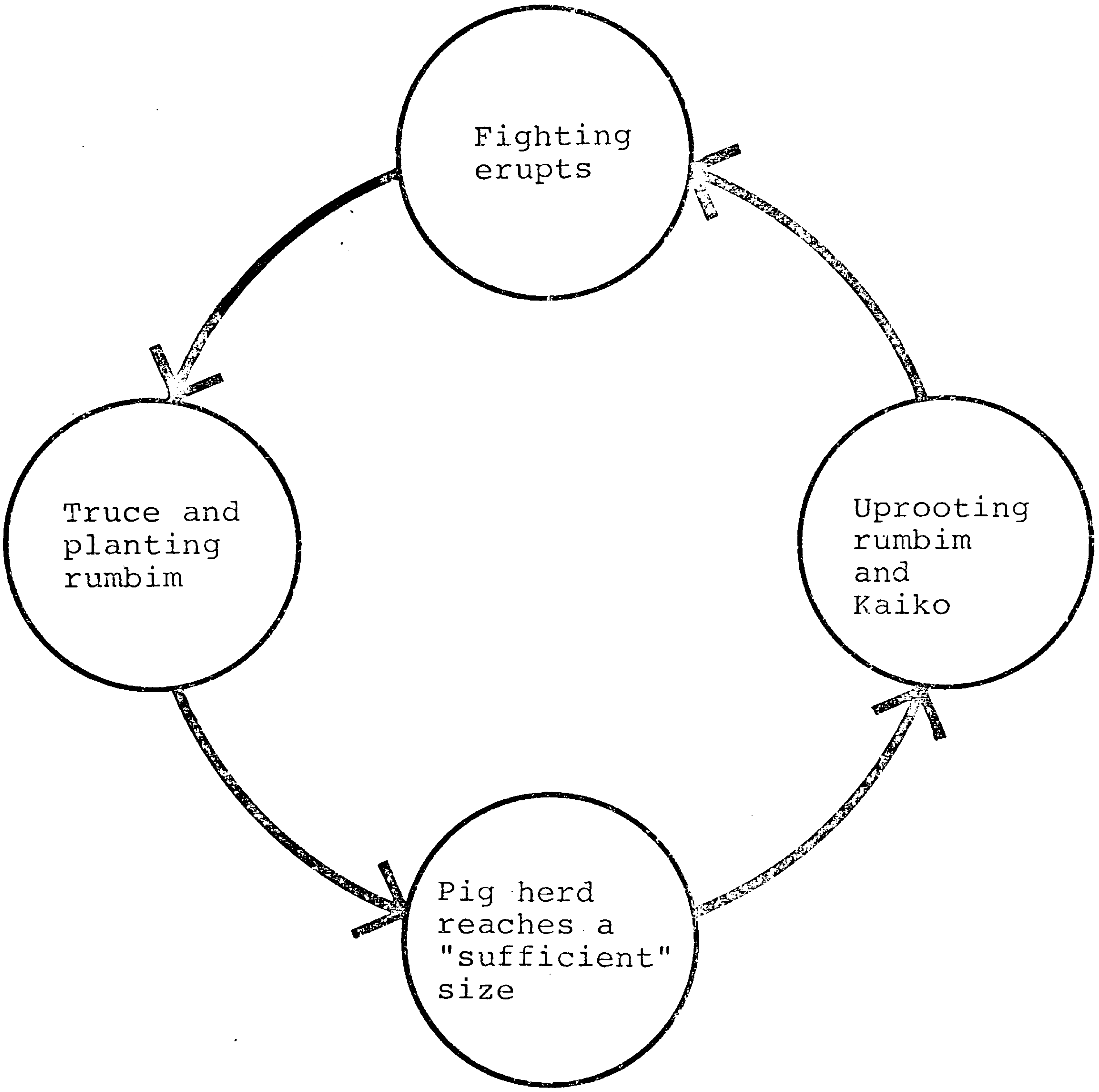


Figure 1. The Tsembaga Ritual Cycle - General Structure.

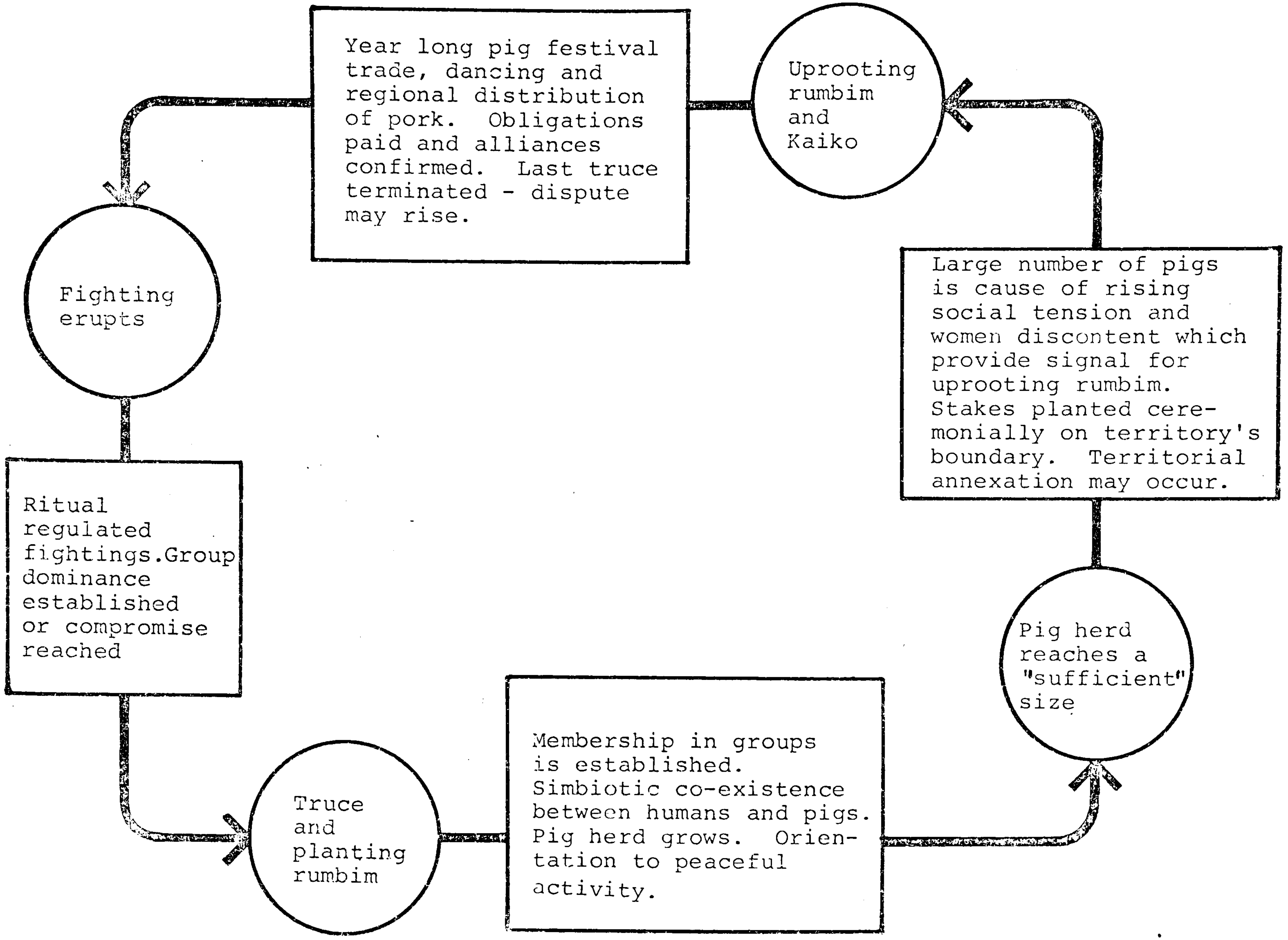


Figure 2. The Ritual Cycle - Transition Points and Characteristics of their Effect on the Whole System.

boundaries claimed by particular groups, as well as to reaffirm alliances for joint territorial defense. The stake planting ritual may also be associated with annexation of new land. This will occur if a hostile group that had been driven out of its own territory during a previous period of fighting did not return to plant rumbim. In such a case, claim can be made to enemy's territory and the stakes are planted in new locations. Otherwise they are planted at the old boundary, thus reaffirming its validity.

Following the uprooting of the rumbim, the pig festival begins with the performance of the appropriate rituals. As previously mentioned, the number of pigs is drastically reduced (by slaughter) during the year-long festival. But the Kaiko is also characterized by large-scale entertainment of friendly local groups who are invited to join the festivities. These festive occasions are marked by ceremonial dancing during which, following the display behavior of male dancers, indirect contact is made between eligible members of the opposite sexes. Actual courtship, however, must await the termination of the Kaiko. The same festivities facilitate trade as well, and men who have assembled for the ceremonies use these occasions for exchanging objects of value.

The Kaiko reaches its peak with a series of events during which most of the pigs are slaughtered. These events, which build up towards the termination of the Kaiko, are associated, among other things, with the abrogation of taboos affecting intergroup relations. The significance of such events extends to the regulation of regional relations as well, as they involve regional distribution of pork through ceremonial presentations, and the payment of all debts and outstanding obligations to friends and allies.

The Kaiko, in summary, does not only act to reduce the number of pigs, but it facilitates mate selection and marriages, as well as the exchange of goods between friendly groups. It affects the regional distribution of pork, the payment of all debts and obligations due, for example, for help in previous fights, and it involves a reconfirmation of alliances in anticipation of new hostilities. The Kaiko affects regional as well as intergroup relations and it brings the whole system to a point where a new cycle can begin.

As soon as the Kaiko is brought to conclusion, truces which had been established after the last round of fighting become invalid, and according to Rappaport, at former times warfare would have normally broken out again within a short time.(37) Like other aspects of Tsembaga life, warfare, too, is regulated by rituals which specify the nature and extent of military activity. Due to the reciprocal need of avenging losses, wars tend to be self-perpetuating. Fighting may be temporarily terminated, however, when one group establishes dominance over another or when antagonists reach a compromise and establish a truce. The ending of warfare and the establishment of truce is associated with the ritual of planting rumbim and participation in this ritual serves to define membership of individuals in a particular group. The ritual signifies peace, and a strict prohibition of warfare, and it reorients the population towards a period of peaceful activity and growth. The pig herd is allowed to increase once more, and the whole system moves toward the point at which conditions will demand that the Kaiko be staged again, bringing yet another cycle to its end.

While Figures 1 and 2 provide an overview of the ritual cycle, Figures 3, 4 and 5 that follow represent the mechanisms involved with regulating the pig population. The general outline of processes which regulate the size of the pig herd is depicted in Figure 3. As shown in this Figure, the size of the pig population depends essentially on the general well-being of the human population in that various misfortunes such as sickness or frequent deaths require constant slaughter of pigs. A stressful existence of humans puts a heavy demand on sacrificing pigs, and the herd can only increase slowly, if at all. When conditions are good, on the other hand, and the human population prospers, the herd can expand rapidly and the number of pigs will increase. A point will be reached sooner or later, however, at which the growing size of the herd will begin to exert pressure on the social system, thus affecting the well-being of the human population. Such pressure will result in a public demand to uproot the rumbim and stage a Kaiko, the ultimate outcome of which will be a significant reduction in the number of pigs.

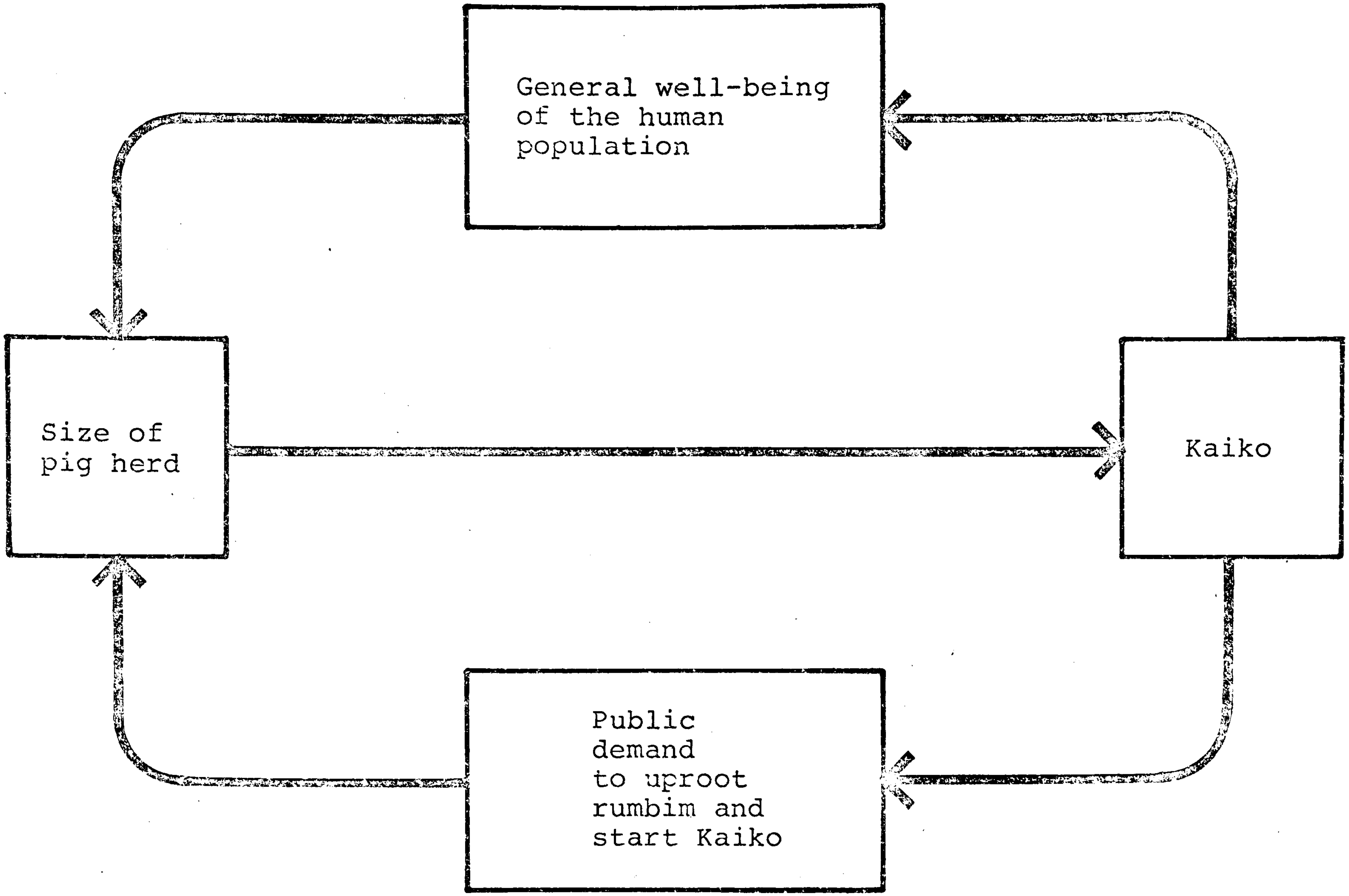


Figure 3. Regulation Effecting the Pig Population - General

Representing a finer resolution level, Figure 4 shows the effects that the size of the herd has on the human population and how these effects relate to the Kaiko. As the diagram indicates, an expanding pig population has various adverse effects on the social system. The combined result is growing agitation and tension which ultimately build up to an intolerable point. Actions are then taken through the Kaiko to bring down the number of pigs. Adverse effects of a growing number of pigs relate to the following:

1. With a growing herd, an increasing physical effort in tending the pigs is required.
2. With a growing number of pigs, more and more incidents of pigs transgressing gardens occur.
3. With an expanding herd, the human habitat becomes increasingly more scattered.
4. A growing herd has the effect of reducing social contact (related to 3 above).

Outcomes of these adverse effects are manifest respectively in the following:

1. A growing discontent of women who have to tend to the pigs and who express their growing burden by voicing complaints.
2. Garden transgression causes damage, occasional killing of pigs, fights between neighbors, and thus an increasing social tension.

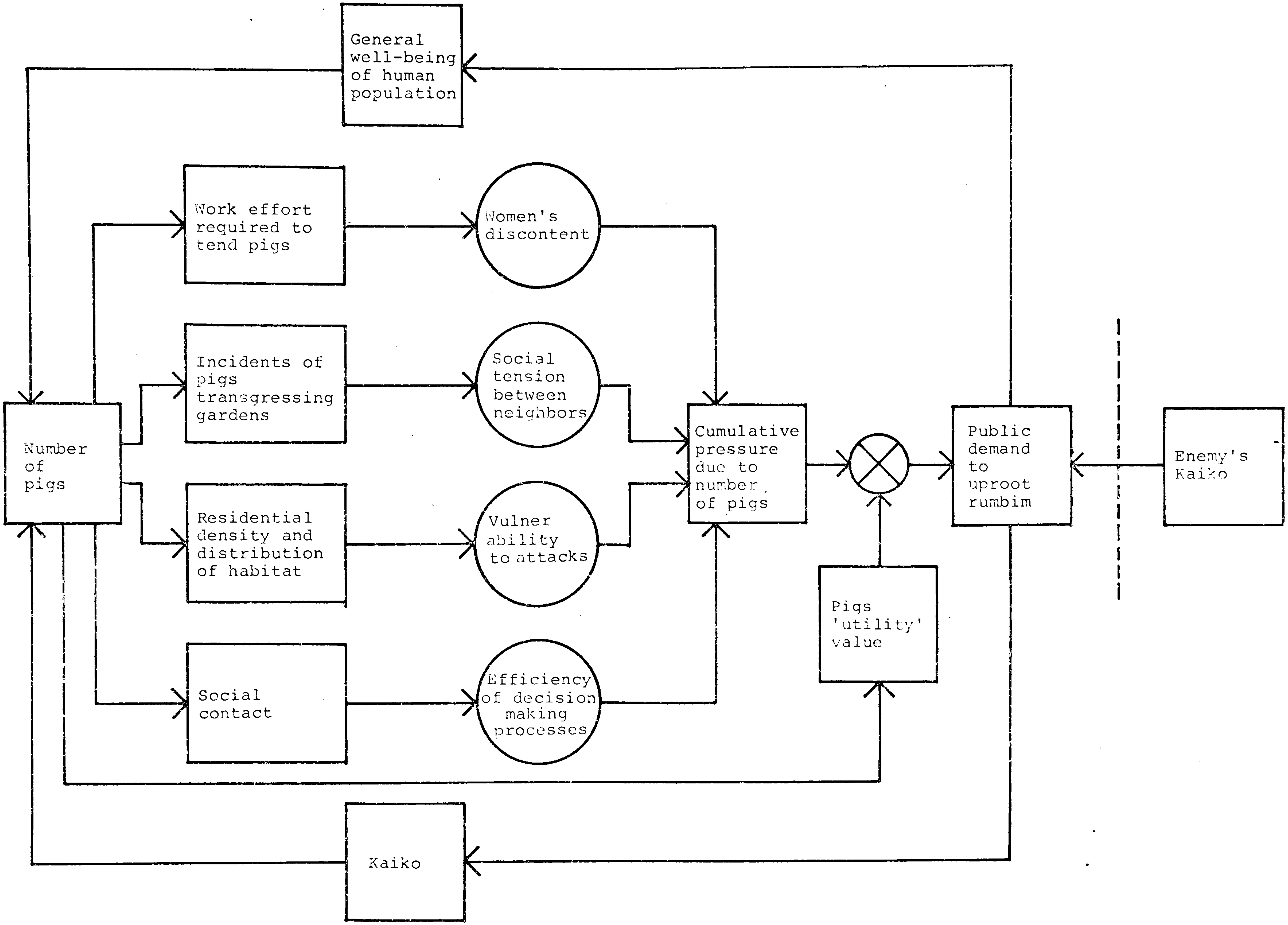


Figure 4. Regulating the Pig Population - General Dynamics

3. As the pattern of habitat becomes more dispersed, local groups become more vulnerable to attack.
4. As opportunities for social contact are reduced, the process of "decision making" becomes less effective due to the fact that consensus is usually reached by informal communal conversations.

All these accumulate to produce a growing sense of social pressure, agitation, and discontent which at a certain point outweighs the overall utility value of pigs. At this point the relationship between pigs and humans changes fundamentally. Pigs cease to be a source of support and become a major source of burden. Their parasitic dependency puts growing demands on human efforts and increasingly more pressure on the social system. Under this pressure a public demand to uproot the rumbim develops and a consensus is finally reached to stage the Kaiko, by the end of which the number of pigs is substantially reduced.

From the viewpoint of another resolution level, the regulation of the size of the pig population is part of a comprehensive mechanism which regulates the combined demand of humans and pigs on the carrying capacity of the territory,(38) ensuring that the carrying capacity will not be exceeded. The general feature of this regulating mechanism is shown in Figure 5. Here, both humans and pigs are regarded as interacting components of one total population.

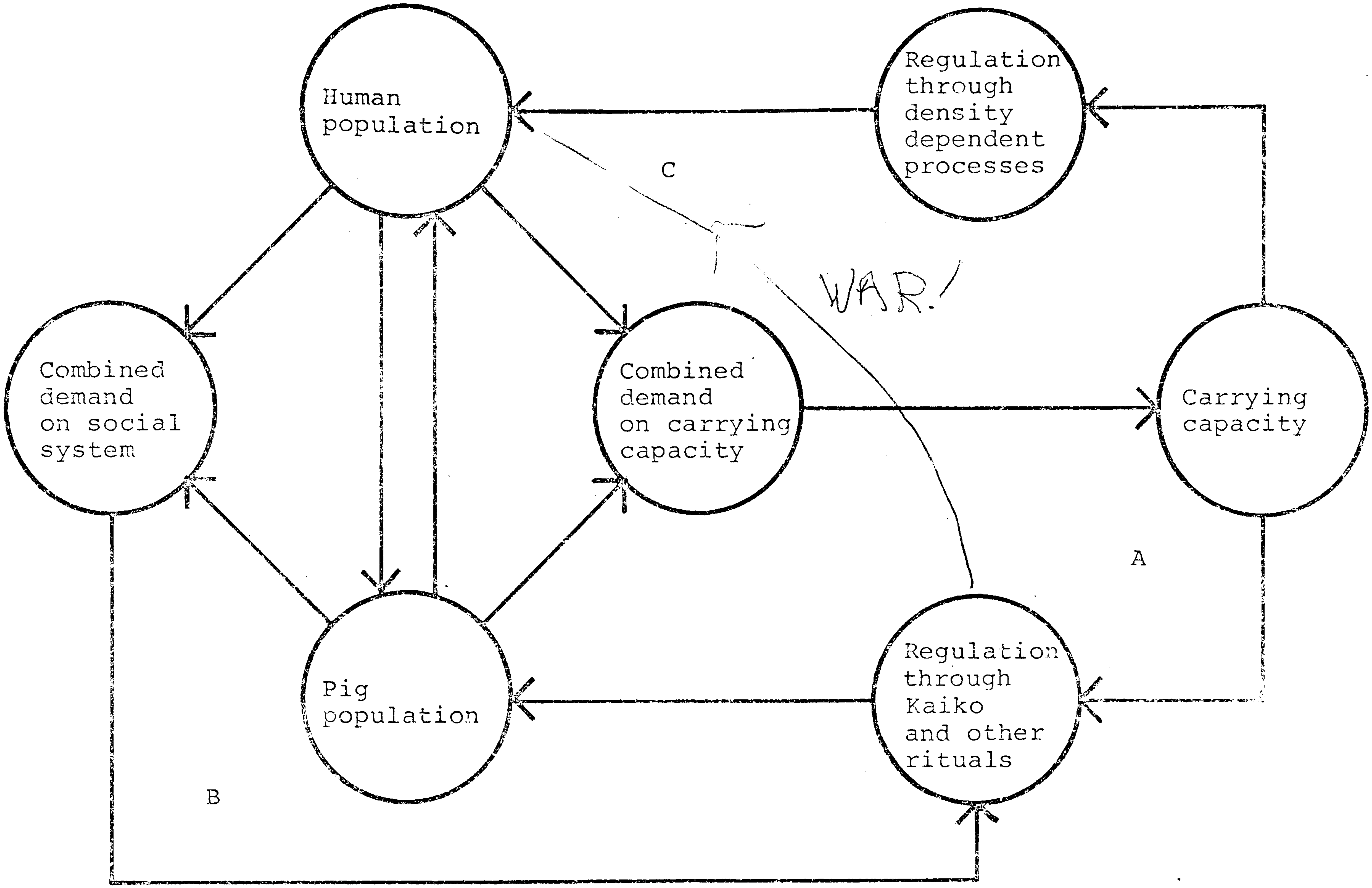


Figure 5. Carrying Capacity and the Regulation of Pig Population

Their relative size makes a combined demand on the carrying capacity of the territory as well as on the social system itself. If the combined demand of humans and pigs were to exceed the actual carrying capacity of the territory, two processes could be put into action in order to restore balance. Firstly, the size of the human population could be kept down through various density-dependent processes such as dispersion, suppression of copulation, and the like (loop C in Figure 5). Secondly, the number of pigs could be reduced through the Kaiko and other sacrificial rituals. One would expect that when the carrying capacity comes under pressure, the mechanism which reduces the number of pigs will be activated first (loop A). The mechanism regulating the demand on the carrying capacity has an inbuilt redundancy, however, which ensures that effective action will be taken before the carrying capacity is actually threatened. This redundancy is provided by the effects that a growing pig herd has on the social system. (These are the same effects which have been discussed in detail with respect to Figure 4 above.) The crucial point is that the accumulating pressure on the social system activates processes leading to the Kaiko and subsequently to a reduction in the number of pigs (loop B), long before the limit of the carrying capacity is reached. The mechanism acts as an important safety device ensuring that the competitiveness of pigs for available resources will be effectively limited, and that the carrying capacity of the territory will not be seriously threatened.

The homeostatic characteristics of the ritual cycle viewed as a whole are also manifest by the structure of some specific classes of activities which are responsible for returning parts of the system to a stable condition when deviations occur. A typical example is offered by Rappaport's interpretation of the way trade and excess wealth affect the regional distribution of population. The homeostatic features of the processes involved are summarized in Figure 6. The diagram represents the interaction of two neighboring populations (from the Simbai and Jimi valley respectively), and it portrays a typical situation as it existed prior to contact with the Australian administration. At that time, the two populations traded their respective primary products --stone axes and salt.

Let us start following the diagram on its left-hand side with the box depicting the population of the Simbai valley. People in the Simbai valley manufacture salt and they generate a demand for stone axes. Axes, in turn, are produced in the Jimi valley by people who cannot obtain salt locally. Axes and salt are thus traded between the two populations, but if the demand for one item is greater than the demand for the other, the difference will be accumulated as excess wealth in the form of objects of value. An increase in the population of the Simbai valley, for example, may cause a significant increase in the demand for axes, resulting in an accumulation of wealth in the Jimi valley. This excess wealth allows men from the Jimi valley to obtain brides from the Simbai valley

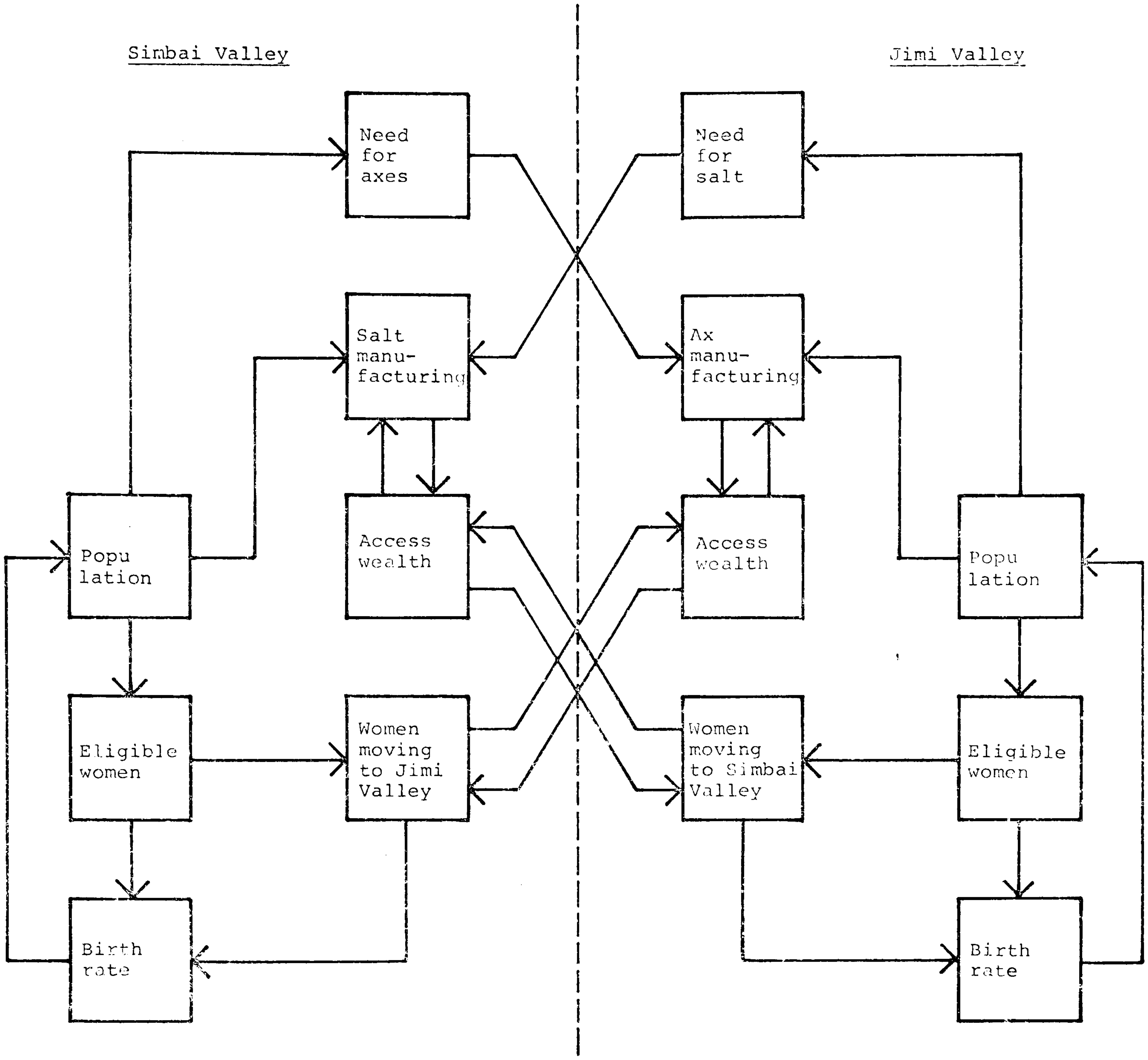


Figure 6. Homeostatic Regulation of Trade, Access Wealth and Population Distribution.

thus affecting the local birth rate. Ultimately, the size of the population in the Simbai valley will fall, as will the demand for axes. In the same way, an accumulation of surplus wealth in the Simbai valley is likely to affect the population of the Jimi valley. Thus, trade and excess wealth, which are mutually dependent, provide a mechanism by which distribution of people in the region is mediated as they affect a tendency to adjust difference in the population dynamics of the two neighboring groups.(39)

1-2.3. The Ritual Cycle--Further Cybernetic Considerations

In the previous section, we have followed Rappaport's description and interpretation of the role of ritual in the ecology of the Tsembaga. As Rappaport has shown, the ritual cycle fulfills an important regulatory role. In its capacity as a regulator, it functions as a complex homeostatic mechanism in that the performance of the various rituals associated with the cycle operate to maintain the system's "essential" variables within the range of their acceptable values.

"The system" has been defined in an ecological or regional context, and its essential variables have been identified with the size of the human population, the number of pigs, the amount of land under cultivation, the general quality of the environment, the severity and frequency of fighting, the density and distribution of the regional population, and so forth. Signals indicating that essential variables are exceeding, or are about to exceed their limits, are conveyed by women's dissatisfaction, increase in social tension, and various other social and ecological manifestations, and the actions which function to restore the system's stability are triggered by specific rituals and are associated with such activities as the Kaiko, termination or initiation of fighting, and so on.

Other important cybernetic features that characterize the behavior of the Tsembaga and the operation of the ritual cycle are brought to light by Rappaport's study. These include the idea that the ritual cycle, in addition to fulfilling a homeostatic function, also operates as a transducer in that it converts changes of states in one part of the system into meaningful information that is made available to, and often affects, other parts of the system. For example, Rappaport points out, the act of uprooting the rumbim provides a well-defined message about the specific state of a particular local group, and it gives a good idea of what action may be expected from that group. Since much of the information conveyed by events associated with the ritual cycle is binary in nature, the operation of the homeostatic regulation that is affected by the cycle is greatly simplified. This binary aspect of rituals means that states of the system are specified unambiguously. It thus reduces the possibility of error by ensuring the clarity of messages and by eliminating the need for selection in securing the appropriate response.(40)

Yet another significant cybernetic feature is exhibited by a redundancy in the structure of rituals and in the structure of decision making amongst the Tsembaga. In both cases, this redundancy is interpretable in terms of McCulloch's model of the functioning of networks having a "redundancy of potential command." (See section D-4 of Appendix D.)

Concentrating only upon the homeostatic characteristics of the ritual cycle and the general problem of regulation in the context of social systems, the most important fact about the homeostatic function of the ritual is the fixed and automatic execution of its typical procedures. When carried out in response to specific events, such procedures maintain (or restore) the system's stability in a way that is mechanically analogous to the aspects of instinctive behavior in animals that are discussed in Appendix D (section D-7). In both cases the concern is with a system that has become adapted to a particular environment. The adaptation is exhibited by activities conducive to the system's survival that are triggered automatically by specific conditions. In this respect, Rappaport's account of ritual regulation in the Tsembaga fits the "organizational model,"(41) and it can be easily portrayed in terms of organizations of related classes of programs, resembling the hierarchies of goal-directed processes that are embodied in configurations of TOTE-like units.(42) From this viewpoint, stable conditions of essential variables in the Tsembaga ecology are identified with specific goal states. In response to discrepancies between the actual and the "desired" value of goal states, specific programs are automatically triggered and their execution has the effect of returning deviating values of particular variables to their stable condition. The corrective action is prescribed by the conventions of the ritual cycle which provide a formula specifying what action should be taken under what conditions.

Because of its particular structure which is characterized by events that follow each other sequentially, the ritual cycle can be described as a sequential program,(43) and components of the cycle can be regarded as subroutines prescribing specific algorithms for actions that should be taken in particular situations. As conditions in the ecosystem change in a cyclical repetitive manner, the appropriate programs are triggered and executed in a sequence of responses that is synchronized with the sequence of changing events. There is, however, a definite control hierarchy contained in this sequence, in that different rituals, or different "programs," relate to different levels that characterize the system as a whole. Thus, while some programs mediate regional relationships, others regulate intergroup processes and yet others affect individual behavior. All these levels interact strongly and they integrate the various aspects of social behavior into a stable and coherent whole.(44)

There is another form of hierarchy involved in connection with specific classes of rituals relating to cases where prescribed actions are organized in stages of intensity or scale. A good example is the class of rituals which regulate fighting. This ritual can be represented as a hierarchy of programs with the goal of mitigating the severity of fighting and keeping the loss of life within reasonable limits. The programs are organized on different levels corresponding to different aspects of warfare. On one level they regulate the frequency of fighting; on another level they provide temporary "stop" rules for fighting, once fighting has broken out; at another level they prescribe stages of confrontations with different degrees of severity. Finally, the programs define actions which are undertaken prior to a fight and which tend to limit its duration. For example, rituals involving all-night dancing, the consumption of pig's fat at dawn, and a strict taboo on subsequent intake of water, ensure, as Rappaport suggests, that combatants will not be able to fight virorously for a lengthy interval.

Viewed as a whole, the ritual cycle is a regulator containing a finite repertoire of programs that specify a set of possible behaviors. It is the specific means by which a particular society has adapted to its environment and the effectiveness of the programs provide a measure of this adaptation. The viability of the Tsembaga as a coherent social entity depends upon a repertoire of actions (prescribed by the cycle) rich enough to match the variety of conditions presented by the environment. In other words, the stability which characterizes the Tsembaga as a social system is due to the fact that regulative procedures mediated by the cycle are capable of providing a "correct" response for each one of the various conditions that are presented to the system in the context of its well defined and isolated environment.

For the Tsembaga, regulation is affected by a homeostatic mechanism, similar in principle to a simple thermostat. The effectiveness of the ritual cycle in regulating the relationships between the various components in the Tsembaga system depends entirely on a totally stereotyped response. The programs embodied in the ritual cycle are fixed, fully specified, and unambiguous and, like a simple homeostatic device, they employ a well defined decision rule. This decision rule determines what corrective action (prescribed by a program contained in the repertoire) will follow which change in the state of the system or its environment. As the environment does not represent essentially novel situations, the rigidity and automatic functioning of the ritual cycle ensure that the possibility of human error in deciding or formulating an appropriate course of action is kept to a minimum. The Tsembaga need only perceive that the system has reached a particular state. Once this is recognized, the ritual specifies what action should be taken. The Tsembaga do not, for example, have to understand (and in fact they do not understand) the real operating principles involved in their activities. (As Rappaport emphasizes, all rituals are directed towards, and explained in relation to, supernatural entities, specifically the spirits, which the Tsembaga assume to be an important part of their environment.)

This stereotype, automatic mode of regulation can be very effective even in cases where complex processes requiring precision and delicacy have to be controlled. For example, as Bronowsky points out,(45) Japanese metallurgy, and especially the art of forging swords which reached a high degree of perfection in Japan by the 9th Century, have always been associated with rituals. Lacking chemical formulae and scientific understanding, the correct repetition of a sequence of complex actions, involving precise control of temperatures and a combination of chemical ingredients, was ensured by following a prescribed sequence of steps which were embodied in the structure of a ritualized ceremony. For this kind of regulation to be effective, one condition is essential, namely that circumstances underlying the processes that are being regulated will not change. The fixed and stereotyped solution can be effective only when the problem posed to the regulating mechanism remains essentially the same problem.

This condition characterizes the Tsembaga world. Changes in the local system are cyclical, repetitive, and contain no fundamental deviations from conditions which have occurred in the past. Once the appropriate programs have been perfected through a long adaptive interaction with the environment, there is little need for further development for as long as the rate of change in the environment does not vary significantly.

Ritual regulation in the Tsembaga is associated with mechanisms by which a fixed systemic structure is maintained. The mechanism involved does not have to deal with the problem of continuous adaptation and it does not have to effect fundamental changes in the system's structure in response to new environmental conditions. The rate of change in the Tsembaga's world is negligible to the point of being imperceptible, and the basic conditions affecting their existence must appear much the same generation after generation. (46) The stereotyped behaviors prescribed by the ritual cycle thus provide an effective survival strategy, and this effectiveness is reinforced by the sacred nature of the rituals. The sanctity that is involved provides a level of "meta-control" ensuring that deviations from prescribed actions that have been proven successful in the past will not occur.

Should conditions underlying the system's existence alter in any fundamental way, or should the system's environment be characterized by a high rate of change, the strategy of following stereotyped actions may prove disastrous. In this sense, the simple homeostatic regulation that is sufficient for maintaining stability in the Tsembaga ecosystem must be regarded as a special case of regulation (although it can be found in a wide variety of systems). The more general case will be associated with a changing environment in which homeostatic mechanisms have to be continuously optimized by an evolutionary process. If there is a significant change in an environment, continuous adaptation will be essential. In such a case, continuous "learning" must be involved in a process in which a system's preferred states are continuously redefined, the "programs" regulating its activities continuously "rewritten," and its manifest behaviors continuously integrated in the context of a new and more comprehensive framework.

It is interesting to note in this respect that, although in the face of it ritual regulation in the Tsembaga has the characteristics of simple homeostatic processes, the system is potentially ultrastable. A new potential variety is being continuously injected into the system by the constant reshuffling of the population that is affected by the exchange of people between local groups. The fixed and relatively static environment precludes, however, the need for change, innovation, or reorganization, and the potential for evolution, which is inherent to the system, is thus suppressed.

In closing the discussion of ritual regulation in the Tsembaga, it may be appropriate to stress, once more, the difference between the specialized "stationary" stability of simple homeostasis, and the more general case of "non-stationary" stability that is characteristic to continuous adaptation and evolution. Any comprehensive view of society which centers around the question of the nature of social regulating processes, and which is directed by a sense of history, must recognize the creative and essentially evolutionary forces that are involved in the dynamics of social systems. Social systems, unless they represent "blind allies" in the sense of Toynbee, are evolving systems. In this sense, they are characterized by a fuzziness of processes, an underspecificity of goals and a redundancy in mechanisms of regulation. These characteristics are in fundamental contrast to the rigid fixity of an insect society, and for this matter of the Tsembaga ritual. It is this fuzziness, underspecificity, and redundancy, which underlie the open-ended process we call evolution.

2. AMPLIFYING REGULATION AND VARIETY INCREASE IN EVOLVING SYSTEMS

2-1. Regulation and Evolution

2-1.1. Evolution as a Type of Stability

Viability of complex dynamic systems inexorably relates to two aspects of systemic behavior which find their expression in the ideas of constancy and change. These two aspects are not incompatible. Indeed, the notions of stability and adaptive behavior revolve, to a great extent, around the problem of maintaining a balance between constancy and the preservation of steady state on the one hand, and change, variability and reorganization on the other.(1)

Constancy and change are essential features of viable existence and they are related to the operation of specific regulation mechanisms; those which maintain critical steady states and those which ensure adaptation and evolution. Both are implicit in the concept of survival and thus in concepts relating to the internal stability of viable organizations, to their integrity as a unity and to the dynamics of their interaction with the world. A self-maintaining constancy is a logical prerequisite to the idea of evolution (2) and, in this respect, it is convenient to regard constancy and the typical mechanisms which maintain it as a starting point, in relation to which change and the mechanisms underlying selective change can be understood.

In the typical viable system that is of interest to cybernetics, constancy is maintained by homeostatic regulation mechanisms. These underlie the self-stabilizing processes which preserve steady state by triggering the appropriate restoring actions returning a system to its "normal" conditions after displacement. For a given system in a given environment, homeostatic mechanisms maintain internal processes in balance and they extend to the system's mode of interaction with the world. In a dynamic environment, however, the very parametric constraints upon which the system's survival is predicated may alter, thus requiring some essential modifications and a restructuring of the system itself. Therein lies the key to evolution and to the related topics of learning, adaptation and development.

While homeostasis and steady state are a precondition for viable existence, evolution can be regarded as a process through which the homeostatic mechanism itself is being optimized.(3) This optimization is a self-organizing, goal-seeking process, with survival being its open-ended goal. It operates not only in order to keep up with changeful events, but even more significantly, in order to produce selective improvements on previous norms. In so far as the optimizing process requires a reorganization of already existing structures, it implies a need to extend the notion of homeostatic stability to a conceptual framework capable of accounting for the dynamic and "progressive" characteristics of evolution.

Such an extension is quite possible, as Beer points out,(4) if we allow for occasional "excursions" from a state of equilibrium in a process which may hit upon other possible configurations corresponding to new levels of stability. The crucial idea is that a given regime of stability is associated with some measure of "survival" success, a "pay-off" function, which is determined by the mode of interaction with a specific environment. The latter acts as an external arbiter, encouraging some configurations and eliminating others. In this manner, selection in the Darwinian sense is affected. Excursions from an established state of stability, (which may be biased by past "experience" and are thus not necessarily entirely random) will either be ruled out as unstable or they may fit an ecological niche yielding a higher pay-off. If the latter is the case, novel sets of states corresponding to parametric and internal constraints will be defined, and a new systemic integration will take place - more survival worthy in some specific sense. Such a new systemic integration will in itself assume typical homeostatic characteristics both in the structure of its internal regime and the mode of its interaction with the world.

From an organization viewpoint, the process is embodied in a hierarchy of control, "control of control" in the sense of Pask,(5) in which the homeostatic stability affected by one level of control is mediated by the operation of a higher level of control. The concept of such a hierarchy is essential when we model the evolutionary process by an organization of goal directed processes reduced to units of control, the procedures they contain and the modalities of their interaction. (See sections D-6 and D-8 of Appendix D). The stratification is needed in order to distinguish between the different contexts of commands, interpretations, descriptions and operations that have to be employed in order to reflect the structure and dynamics of the regulatory mechanisms that underlie an evolutionary process.

The entire arrangement can be envisioned as follows. On one level, there is a homeostat or a group of interacting homeostats operating jointly on a specific environment so that a particular stability is brought about and maintained (reproduced over time). This interaction is ultrastable in Ashby's sense, and the stability involved is contingent upon the intervention of the next, higher level of control. On this higher level, the environment acts as the context from which an external "reinforcing" signal is derived. The value of this reinforcing signal constitutes the pay-off function which acting as an input to the higher level control guides its selection strategies. It provides the criteria for success by which stability configurations "presented" by the lower level are selected, established and reinforced. (For the ikonic representation of an evolutionary process embodied in a control hierarchy, see section D-9, Appendix D).

Evolution, from this viewpoint, is characteristic of a particular type of dynamic behavior in systems, reflecting a particular aspect of the logic of mechanisms.(6) It corresponds to a specific type of regulation and it is embodied in a particular kind of organization. This statement is significant in so far as it stresses the idea that evolution is a type of stability, and that as such, it is a general condition typical to environments characterized by a particular structure of constraints.

The organization underlying an evolutionary process can be abstractly represented in various ways. In general, it can be depicted by a system of interacting goal-seeking elements having to secure a stability, namely their own survival, in an environment representing a given set of constraints. Evolutionary activity in such a system is a consequence of changeful environmental conditions and a redundancy in the structure of the system itself. This redundancy can be regarded as a source of active variation and it implies a potential repertoire of behaviors which can become manifest as conditions change with time. As long as redundancy is maintained, the system has self-organizing properties in the sense of Von Foerster. (See section C-8, Appendix C).

Some additional ideas are important.(7) Firstly, survival must be conditional. It is not guaranteed and it will be enhanced by some conditions and some behaviors but not by others. Secondly, overall goals in the system must be underspecified and generally open-ended, implying a tendency for "exploratory" behavior. In the process of seeking for a viable stability, various organizations and modes of behavior will arise, subject to satisfying the conditions for stability under existing constraints. Favorable organizations and modes of behavior will be allowed to persist (survive, reproduce, remain stable) and those that entail an improvement will be encouraged to develop, thus generating a trend that an observer would deem "evolutionary".

Generated by a progression of time related organizations, the evolutionary trend represents the "necessarily time dependent character of a self-organizing system".(8) The sequence of steps that is implied obtains its coherence by virtue of the topic an observer entertains. Some ambiguity may exist, however, as to the precise boundaries of the evolving entity since the shifting stability that is involved obscures the distinction between the evolving organization and its environment. On the level of an abstract representation at which evolution is regarded as a general process, the essential features of reproduction, variation and selection appear as unifying principles. The particular characterisitics of mechanisms through which evolution is mediated will vary, however, with specific identifications. It is when we focus on an actual "real-world" organization that such mechanisms will assume specific identities, coinciding with specific embodiments.

2-1.2. The Evolutionary Perspective and the Cybernetic Paradigm

Scientific discussions of evolution since Darwin have centered around essentially biological issues related to the emergence and subsequent history of species. A broader concept of evolution as a creative principle embracing all cosmic phenomena, including but not limited to terrestrial forms of life, has been advocated by religious mystics, notably, Teilhard de Chardin (9), but such visionary contributions remain alien to established scientific disciplines. Recent developments in the physical sciences, however, have articulated the principles governing the evolution of complexity in physico-chemical systems. These principles, formulated in the field of non-equilibrium thermodynamics (10) have been applied to an analysis of some biological processes (11) and they have been used by way of analogy to discuss the evolution of socio-psychological and conscious phenomena as well.(12)

The formulation offered by non-equilibrium thermodynamics holds that the increase of complexity and organization in physical systems is a consequence of specific kinetic principles and that the concept of evolution in physics and biology are reconcilable under a single physical law.(13) This formulation can be interpreted as reaffirming the intuitive concept of the unity underlying natural phenomena, but since it involves mathematical concepts describing the dynamics of energy flows subject to strictly defined constraints, its "extrapolated" projection into the domain of socio-psychological systems may be questionable.

An approach taken by cybernetics, on the other hand, offers a different perspective which, by emphasizing organizational aspects that are independent of material considerations, is free of similar limitations. The approach involves a formulation of a concept of regulation linking the notion of survival, in its broadest sense, to ideas of information and control. In this context, evolution can be regarded as an outcome of a particular "survival strategy", applicable to a specific constellation of circumstances and subject to the general laws of regulation. These laws are conceived on a level of abstraction which makes their transfer across systemic boundaries particularly convenient. The cybernetic paradigm can therefore contribute significantly to a unified view of evolution and it provides for a consistent interpretation of both the dynamics of special case evolutionary process and the overall direction of evolutionary trends.

From the cybernetic viewpoint, a complex dynamic environment puts a definite premium on an increase in potency of regulation capabilities. Thus, a perception of the world as a hierarchy of structures, differentiated by discontinuities and characterized by an increasing order of complexity and organization (14) obtains a specific functional meaning. Such a hierarchy can be regarded as a stratified organization of controllers interacting such that across its levels regulation is amplified.

2-2. Regulation for Effective Viability

2-2.1 The Cybernetic Formulation

A regulator is a mechanism which interacts with a system to bring about, or maintain, a particular outcome. This outcome corresponds to a goal representing a condition of stability for the system under regulation. From the cybernetic viewpoint, a condition of stability in a system implies the functioning of a regulator. The latter can be identified with a specific part of a system, the brain in a mammal, for example, or it can be regarded as a source of action external to a system, as in the case of selection in evolution. Whether a regulator is identified with a specific part of a system or with a source external to it depends, to a great extent, on lines of demarcation imposed by an observer. Actual boundaries may be ambiguous, especially in cases where there is no clear cut physical partitioning.

Regulators in the real world span a broad spectrum of types and mechanisms through which control is mediated vary widely in their characteristics. They may, for example, involve direct mutual effects of interacting chemical processes, as in the body's physiology, or be affected through specialized communication channels carrying specific signals, as in the central nervous system and in various man-made electronic devices. They may be mediated by complex behavioral patterns as in ecologies of animals, or they may be associated with intricate symbolic relations as is typical to social systems, human in particular. The subject matter of regulation is thus extensive and it relates to many diverse activities in physiology, psychology and sociology, ecology, economic affairs, engineering and more. The cybernetic formulation provides an abstract representation which highlights the fundamental features common to all.

The central idea is that regulation achieves a goal in the face of a set of disturbances. The approach is due to Sommerhoff and Ashby, (15) who defined the process of regulation as a function of five key variables and the manner in which they interact. These variables include a regulator, a regulated system, a source of disturbance, a set of possible outcomes and a set defining desired outcomes. The role these variables play in the process of regulation is specified as follows (16): for a given situation, there is a total set Z of all possible events which may occur whether restrictions are applied or not. Of these, a sub-set G defines desired outcomes - those that correspond to a condition of stability for the system under regulation. In addition, there is a set R of events in the regulator, a set S of events in the system which is being regulated, and a set D of disturbances. Events in D produce conditions in S that cause outcomes to be driven out of G. Effective regulation is achieved if for a given value of D, events in R and S relate such that the outcome is bounded by G.

The relations between disturbances and the actions taken by a regulator can be formalized in terms of game theoretic concepts.(17) From this viewpoint, a set D of disturbances d_i is countered by a set R of responses r_j producing a matrix of outcomes z_{ij} from a set Z of possibilities. The values taken by D and R correspond to a pair of moves selected by each of two players and the table of outcomes is identical with the pay-off matrix of game theory which specifies values of some desired commodity that is assigned to each move. A successful outcome will encourage a player to retain a particular strategy whereas a failure to achieve a desired payoff will cause a change of strategy in the following move. As before, of all the possible entries in Z, obtained by the interaction of D and R, only a subset G contains acceptable outcomes representing values which are compatible with a system's "essential variables". R is considered an effective regulator if it can produce a counter action r_j for each d_i in D keeping the outcome within G.

The nature of the relation between D, R, Z and G is such that the concept of regulation implies selecting from a few possible actions the one most likely to achieve a goal. This selective aspect is a dominant feature of regulation especially in complex dynamic systems where regulation takes its more interesting and active form. Since effective selection depends on the availability and processing capacity of information, there is an obvious sense in which communication and information play a central role in regulatory processes. Ashby has stressed the intimate relation between regulation and information (18) and he had shown how regulation depends upon information transfer between pertinent system's components. From a qualitative viewpoint, regulatory actions are subject to information about specific disturbances, about the state of the system which is being regulated and about the outcome. This relation can be given a precise quantitative expression using information theoretic concepts,(19) and various regulatory schemes can be reduced to the characteristic structure of their respective information processes. For example, error-controlled regulation can be regarded as a special case of regulation in which R receives its information from variations in the outcome. It can thus react only after the effect of a disturbance has been manifest. In other types of regulatory schemes, R is provided with an information channel directly from the disturbance, making "anticipatory" strategies possible. In such cases, the regulator is activated before the actual effects of a disturbance have been registered and its counter actions are directed at the source of disturbance itself.(20)

2-2.2 Limits on Regulation

According to the formulation given above, the process of regulation can be regarded as a sequence of events in which R selects a move r_j from a finite repertoire for each value d_i taken by a disturbance from the set D. The variety in R's repertoire of actions puts a limit on its capacity as a controller since in order to regulate effectively, the variety of actions available to R must be at least equal to the variety in the disturbance. This concept is fundamental to the theory of regulation and it is expressed in Ashby's law of "requisite variety". The law states that for a given variety in the disturbance, only variety in R can force down the variety in the outcome.(21)

This dependency can be interpreted in terms of communication theory, in which case, the process of regulation is related to the flow of variety between R, D and Z. From this viewpoint, D threatens to transmit its full variety to Z. R's function as a regulator is to block the transmission of variety from the disturbance to the outcome, so that a "desired" variety in Z is maintained. The crucial point is that without R's intervention, the ultimate variety in Z would be large. With R's response it can be reduced. R can thus be regarded as a channel of communication between D and the outcome, and Ashby's law is extended to its more general form stating that "R's capacity as a regulator cannot exceed R's capacity as a channel of communications".(22)

The law of requisite variety puts an absolute limit on the amount of regulation which can be achieved by a regulator with a finite capacity. The implications to the concept of viable organizations and particularly to the concept of adaptation are important. A viable system that is adapted to its environment can be regarded as a successful regulator in the sense that the repertoire of its actions (or behaviors), matches effectively the variety in the disturbances threatening its stability. The concept of selection can be interpreted accordingly as entailing a process which operates to encourage an appropriate match between a regulator's variety and the variety in its environment. In a complex dynamic world it will favor the formation of high variety regulators.

2-2.3. Amplifying Regulation, Strategies for Effective Viability and Variety Increase in Evolving Systems

The need for variety in the regulator is greatly reduced if the environment is characterized by fundamental regularities such as a continuity or a repetitive pattern of events. Thus, when a regulator faces a large and complex world, a situation that is common in biology as it is in social and economic affairs, there are circumstances which make effective regulation actually possible even with a relatively low variety.(23) Nevertheless, a system may be exposed to patterns of disturbances requiring an augmented regulation capacity. In such a case, an extension in regulation potential will be essential, and if systemic disintegration is to be avoided, the regulatory capacity will have to be increased until it becomes adequate.

The limitation implied by the law of requisite variety prohibits any direct increase in the capacity of a regulator but it does not rule out supplementation. As Ashby has shown, if there is a continuity in an environment, a number of regulators can be linked in stages to form a more potent regulator with an increased overall capacity. When regulation is applied in stages, for example, when a regulator R_1 uses its selective power to form another regulator R_2, the capacity of the latter need not be bounded by that of the former. The possibility thus exists that a small amount of regulation properly exercised at one stage will make available a higher regulation potential at the next stage. The procedure can be repeated over a number of steps with the result that a significant increase in regulation capacity is achieved, the process as a whole showing an amplification.

The possibility of amplifying regulation has played a major role in the evolution of stable organizations on earth where circumstances favor the formation of regulators that mediate local stabilities, selecting for those, that are particularly effective in securing a viable survival under a wide range of dynamic events. This condition in itself, is sufficient for explaining the persistent tendency of forming stratified organizations of increasing complexity, since only through such organizations an increasing advantage in regulating capabilities can be achieved. In the terrestrial environment this tendency has been manifest in the emergence of a hierarchy of organizations ranging from the simple chemical elements to the genetic material and whole ecosystems, encompassing the myriad organisms and their societies, and including a host of different mechanisms all of which contribute to the end of ensuring "survival". Each level in this hierarchy corresponds to a class of regulators and these become more potent as they ascend the scale of complexity. Evolution is the process through which such a complexification is achieved, and in this sense, it can be regarded as an essential regulation strategy for achieving stability in a dynamic environment in which the context for stability is changing.

Depending on underlying conditions, various methods for achieving stability are possible. For example, if the environment is simple, meaning that the pattern of its characteristic events is predictable, a regulator can be built as a physical barrier for blocking the effects of disturbances, or it can be made to embody a set of decision rules specifying an appropriate counter-action for each disturbance. Both methods require an ability to specify all disturbances in advance and they imply building into the regulator a variety which would exactly match all contingencies. This regulation strategy is manifest in special cases of adaptation where the range and magnitude of variations is sufficiently consistent to make it adequate.

When the pattern of disturbances is particularly complex, or when it is constant for too short a time, computation of all possible configurations may be impractical. In such a case, an advantage can be gained if the regulator is made to incorporate a large amount of variety, and if instead of a fixed set of rules it will contain an underspecified provision for modifying internal states in a search for a match with specific conditions as they occur. This is the more general method of adaptation by ultrastability. As a regulatory strategy, it can be greatly enhanced if it is directed not only towards "experimental" modification of internal states, but also towards forming linkages with selected parts of the environment so that new organizations incorporating a higher variety emerge.(24) Here in particular, a significant amplification of regulation capabilities can be obtained. The increase in variety that is involved is typical to the evolutionary process. It is slow in biological evolution where it is manifest in the emergence of increasingly more complex organisms, it is made more rapid by simple forms of learning, and it is accelerated even further, becoming more flexible and richer in scope, in the symbolic environment of culture and ideas.

A distinction can be made, accordingly, between three major and basically different regulation strategies. The simplest involves a precise specification of contingencies that is manifest in a mechanical adaptation or the incorporation of a fixed decision rule in a simple homeostatic mechanism. The second involves adaptation by ultrastability where a sufficient amount of variety is "built" into a system so that changes in its environment can be matched by appropriate internal modifications, even when a specific decision rule is not available. The third is adaptation by evolution. As a strategy for ensuring an effective viability it involves incorporating additional variety from the "environment," forming a new and more complex "unity". The latter corresponds to a new level of systemic integration which is marked by an increase in regulating capacity, and which is subject to selection for some specific survival advantage.

3. EVE-1: A SIMULATED ECOLOGY WITH SOME CHARACTERISTICS OF EVOLUTIONARY PROCESSES

3-1. Introduction

3-1.1. Simulation of Evolutionary Processes

"Eve-1" is a computer model of a simulated "ecology" in which various dynamic processes occur, some of which are interpretable as showing characteristics of evolutionary behavior. In the general philosophy of its approach, as well as in its structure and its basic logic, the model relates to various other typical cases in which simulating aspects of evolution has been attempted by other workers. Like some of these attempts, the model presented below strives to capture the essence of a general process rather than to describe a particular "real" system. In this respect it is not context-specific, and the behaviors that are observable in the different runs that were performed can receive various interpretations depending on pertinent identifications. Of these, biological and sociological interpretations are the most obvious, and some such interpretations are stressed or implied in the context of describing the model and the results that were obtained through simulated experimentation with its behavior under various conditions.

In recent years there have been numerous attempts at simulating evolutionary processes, attempts that were greatly stimulated by the advent of large, reliable, and fast digital computers which provide a particularly appropriate tool for such experimentation. These attempts have taken different approaches and they have addressed themselves to a large variety of problems, some of which do not deal directly with the specific problem of evolution, but all relating to questions that, in one way or another, are relevant to the understanding of evolutionary processes. Thus, the various efforts involved include such diverse items as simulating problem solving and game playing systems, modeling various aspects of cognition, pattern recognition and learning as well as adaptive and predictive control systems, self-reproducing systems, development and growth processes, self-organizing systems, and more. In addition, there are evolutionary models addressing themselves to problems of evolution specifically.(1)

Various arguments in the literature have been questioning the real effectiveness of such attempted simulations in actually replicating a true evolutionary process. Pattee, for example, points out that in spite of the complexity and sophistication of many of the models that have been developed, "their evolutionary potential has been non-existent or disappointing."(2) The disappointing performance of evolutionary simulations, he feels, relates particularly to the problem of the origin of life and to the more general question of generating novelty and new levels of control in hierarchical organizations. The difficulty is clearly in explaining and replicating such phenomena that are usually conceived of as "spontaneous" emergence of new properties in complex organizations.

It may well be, however, that the problem is not technical but philosophical in nature, having to do with the approach to the question of evolution and of replicating evolutionary processes, and thus with what is actually expected from evolutionary models. There is clearly a definite sense in which an actual evolutionary process cannot come entirely under the strict control of the experimenter. By its very nature, the process is incompletely determined. The underspecificity that is involved is quite fundamental and it cannot be circumvented by a simple-minded attempt at simulating an actual complex evolving system, no matter how complex the model (program) involved. (There are obviously practical limitations.) It is quite possible, however, to abstract the relevant principles and to construct a dynamic process, in a computer or otherwise,(3) which will mimic the essence, or some selected aspects, of evolutionary behavior.

The behavior produced by such a model may thus help reveal the working of the mechanisms which underlie evolution, and it can be particularly useful for gaining a better understanding of specific evolutionary processes that occur in nature with which a correspondence can be shown. Furthermore, it may be especially helpful in articulating those characteristics which are invariant to evolution in general. Note the difference in approach. The goal is not to simulate a particular system that is evolving, but to abstract the principles involved in evolution, embody those in a dynamic model the behavior of which may then be subject to interpretation and identification with the appropriate behaviors that are observable in nature. The identification itself is a function of demonstrating a correspondence which may be on the level of a metaphor, an analogy, or an actual isomorphism.

The point is subtle but important and it was made clear by Pask when he pointed out that questions of replicating evolutionary processes can be approached on three different levels: highly abstract, particular, or intermediate.(4) On the one extreme there is the entirely abstract level typical, for example, to the approach taken by Ashby when he suggests that self-reproduction is a concept of great generality, transcending the specific reality of the biological world, and having to do with a well defined concept of equilibrium in generalized dynamic systems.(5) Ashby has shown that reproduction can be regarded as a special case of adaptation to a particular class of disturbances and thus that the particular stability that is involved can be described fully by the abstract concepts of the theory of mechanisms using the logic of sets and mappings (see note 16, Chapter 1). These, it will be recalled, contain no reference to the actual physical characteristics of a particular system.(6) Similarly, the gist of this entirely abstract conceptioning is manifest in Ashby's powerful statement that "every isolated determinate dynamic system obeying unchanging laws will develop "organisms" that are adapted to their "environment."(7) When there is an observable trend of increasing efficiency in such adaptation, an observer will be inclined to speak about evolution.

On the other extreme, Pask points out, there is the approach which focuses attention on a particular "real" system. The system may be a particular population of animals, a specific society, or processes that occur in a brain. It is in such cases, when the system under consideration is intrinsically complex and dynamic in a self-organizing sense, in other words, when evolutionary events constitute an important feature of its behavior, that modeling by straightforward simulation becomes impractical. The complexity and inherent uncertainty which an experimenter will face preclude a precise replication of the process under observation through the setting up of a detailed one-to-one correspondence between the actual system and the model, and the experimenter may therefore have to resort to other techniques. For example, he may choose to study the system's behavior statistically as in the case of Wilkins' model of social homeostasis.(8) Such an approach, however, will gloss over the operating mechanisms which underlie evolutionary processes.

Finally, there is what Pask refers to as the "intermediate" approach which occupies a level between the entirely abstract and the particular. The basic ideas involved have already been alluded to above. It is this approach which is characterized by an abstraction of the basic principles underlying the essence of evolutionary processes. Such principles are then embodied in a set of rules which regulate the interaction of simple abstract entities (simple automata, finite state machines, or sets of numbers, as the case may be), constituting the basic elements with which the model is constructed. The behavior or organization that is thus generated is then open to interpretation which, as we have already seen, depends on identification with "real" systems that exhibit a similar behavior.

Eve-1, the model that will be described below, belongs to this class of simulations. The advantages of the approach are clear. It can be used when a study of an actual evolving system is impossible due to complexity and/or temporal constraints; the abstraction involved, though basically simple, can in itself be designed to embody an arbitrary complexity and thus one model may yield a wealth of diverse behaviors. Finally, the fact that the model depends on the abstraction of basic principles means that the essence of such principles and their effectiveness in explaining observed phenomena can be studied without being confused with those specific details that characterize an actual system (materiality for example) but which may not be directly relevant to the logic and dynamics of the process itself. It may thus be particularly useful in testing hypotheses about the working of mechanisms that underlie evolution.

This particular approach is apparent in several simulations of developmental and evolutionary processes that are described in the literature. Typical examples are Burks' discussion of "growing" automata,(9) as well as Apter's simulation of developmental processes, where "Turing machine"-like automata are used to generate various growth processes.(10) There are models advanced by Barricelli who uses the interaction between numerical entities to generate evolutionary processes.(11) There are simulations developed by Fogel, Owens, and Walsh, where finite state machines go through successive steps of reproduction, mutation, and selection, replicating an evolutionary process which results in an increased ability of such machines to predict events in their previously experienced environment.(12) There is a model described by Glushkov in which simple automata mimic biological evolution and the formation of species,(13) and there are models developed by Pask where similarly conceived automata interact to generate a dynamic behavior through which processes such as reproduction, differentiation, induction, and population density control can be studied.(14) In its spirit and basic structure, Eve-1 owes much to the latter, and although different aspects of evolution and of ecological dynamics have been emphasized, the model can, in fact, be regarded as a variation on and a continuation of Pask's original experiments.

3-1.2. Conditions Underlying Evolution

Most simulations of evolutionary processes reflect the fundamental fact that the basic conditions underlying evolution are exceedingly simple. These basic conditions are central to Darwin's theory which maintains that the prerequisites for evolution demand a dynamic continuity maintaining the integrity of a given entity, a variation in its structure, and a selective process that operates upon it. Such conditions entail a differentiation between a focal entity, an organism, for example, and an environment in which it exists and in which evolution takes place. If such an entity is associated with mechanisms of continuity which preserve its integrity over time (reproduction, for example), if there are mechanisms of variation operative which produce changes in its structure thus introducing new variables, and if these are subject to environmental selection which reinforces trends that are particularly survival worthy, inhibiting those that are not, an evolutionary process may result. If it does, it will be manifest in a measurable trend progressing through a succession of iterative reproductions, variations, and selections, the product of which relates to an overall optimization of the system's performance with respect to its overriding goal, namely--survival. Such an optimizing trend is a function of the system's interaction with its environment and in this sense evolution is seen as a process by which systems develop, are modified and optimized in relation to the specific conditions of their particular environment.

Various means can be used to embody the basic conditions referred to above in simulating an evolutionary behavior. For example, in Barricelli's model,(15) a process similar to a typical Darwinian evolution is obtained by using numerical entities which "exist" in a computing environment. The properties of the specific numerical entities used and the behavior they can generate are specified by a set of rules embodied in a computer program. They are thus entirely under the control of the experimenter. The crux of the matter is that a class of numbers can be so defined that they will generate a process of self-reproduction. To this process a mutation rule is applied (in cases when two numbers collide in the same space) with the result that variability is introduced in the form of a new number, different from the two colliding ones. In this manner both conditions of reproduction and mutation are satisfied and as the process continues through a succession of steps, numbers which have a greater survival value under the rules specifying their universe will "survive" (be selected) and dominate the environment as other less "fit" numbers are eliminated little by little.

In a subsequent and more elaborate experiment, Barricelli(16) used similar numerical entities to represent a genetic code where the latter is interpreted as a program specifying a survival strategy. This strategy is related to a particular task that simulated organisms have to perform. In this case, it is applied to deciding on a move in a simple game ("Tac Tix"). Once again there is a provision for "mutation" by which strategies can be modified when collision between two numerical entities occurs. Selection for the best strategy with respect to the game is applied, and the overall result shows an evolutionary improvement in game performance. This is interpreted as an improvement in performing operations essential for survival which is achieved through an evolutionary process.

Another example is offered by the model proposed by Fogel, Owens and Walsh,(17) where the same principles of iterative mutation and selection are used to generate evolutionary processes although they are embodied in a different method. In this particular case an evolutionary approach is chosen for a simulation of intelligent behavior where the latter is related to an ability to predict the behavior of an observed environment. The environment consists of a sequence of symbols to which a finite state machine is exposed. At each time interval the output of the machine is compared with the next input signal and a match between the two, a correct score, provides a measure of the machine's ability to predict its environment on the basis of the symbols it has previously experienced. From this machine an "offspring" is then derived and a mutation rule is applied to this derivation. The mutation process takes the form of producing a modification in the parent machine with the result that the offspring is made to differ from it in some specific respect. This modification may affect the state transition, the number of states, and so forth.

The offspring machine which is thus derived is subsequently exposed to the same sequence of symbols and its prediction capability is tested. If its score equals or is higher than that of the parent machine it will survive and be used to generate new offsprings, otherwise it will be discarded and the original parent machine will be used again. In this manner, successive generations of finite state machines are obtained and this succession is characterized by an overall evolutionary trend that is manifest in a measurable increased ability to predict the already experienced sequence of symbols representing the environment. Selective processes, the authors point out, can be severe or more relaxed. In the case of the former, only one parent machine exists at a given time and when an offspring is derived the one which shows evidence of a better performance will survive while the other will become extinct. In the case of the latter, there are always a few machines existing simultaneously. From one of these an offspring is derived and if it scores successfully, it will replace that machine the performance of which is lowest in the group. The model also provides for production of offsprings by "mating" two or more machines, thus enhancing the evolutionary process by retaining successful traits through a combined "majority rule."

In yet another approach, exemplified by Pask's model,(18) selection is applied to simple automata on the basis of success in the task of capturing a basic commodity, which appears in the environment and from which the fabric of these automata is synthesized. If such a commodity is scarce, competition may result and variants which show an advantage in this competition will thrive, inhibiting the development and survival of others. Survival thus depends on inherent capabilities and behavioral patterns which are particularly suited for specific environmental conditions and these may be such that they will favor cooperative behavior between automata which by correlating their strategies and activities increase their overall survival efficiency.

Notwithstanding the specific method used, the basic principles of reproduction, mutation, and selection are central to all these models. A point which must be emphasized, however, is that these basic conditions are general in the sense that they do not apply to biological phenomena alone. The latter is but a specific manifestation whereby reproduction takes its known biological forms, mutation is manifest in genetic variations, and "natural" selection operates on phenotypes. In the biological world, successful selection is normally measured in terms of the relative rate of producing new viable offsprings. It operates by "reinforcing" successful mutations thus guiding life forms towards the underspecified goal of ever-increasing efficiency for more effective survival. The whole process is embodied in the specific properties of protein molecules, especially nucleic acids, which as Bonner points out,(19) are complex enough to allow for processes of reproduction and of minor variations in molecular structure that are repeated in subsequent generations.

But there is no need to assume that evolution is restricted to the biological domain. A general theory of evolution must be regarded as a theory about a general process and thus the uniqueness of biological evolution is limited to the fabric of its mechanisms but not to the principles underlying their operation. This is precisely the point that emerges out of the theory of self-reproducing and evolving machines, a theory which demonstrates that reproduction and evolution are possible in generalized logical environments in which certain constraints are operative.(20) Thus for example, on the level of underlying principles, there exists a definite correspondence between biological evolution and "symbolic" evolution where the latter is viewed as the specific domain of cognitive processes in which concepts, or procedures for control and computation evolve.(21) Fogel, Owens, and Walsh(22) make an important comment about this correspondence when they stress the logical similarity that exists between natural evolution and the scientific method. Individual biological organisms, they point out, may in fact be regarded as hypotheses concerning the characteristics of their environment. Like hypotheses in science, they will survive only if "successful." In conclusion one would add that the claim for generality which underscores such correspondences is particularly significant because it provides a logical link between the processes of biology and the "cultural," abstract domain, in which much that is relevant to psychological and social evolution takes place.

3-1.3. The Role of Coalition Formation and Cooperative Interactions in Evolution

Most discussions of evolutionary processes, biological or otherwise, accept the basic Darwinian premises which regard self-reproduction, random mutations, and selection as the fundamental mechanisms the combined operation of which is essential for explaining evolution. Nevertheless, a significant number of critics(23) have been arguing that the Darwinian theory is lacking in that while its basic premises are indeed a prerequisite for evolution, they are not sufficient in themselves for actually explaining the rise of complexity and great diversity characterizing the evolution of life.

Problems seem to relate to both temporal and qualitative aspects of evolution. With regard to the former, Beer,(24) for example, points out that rough calculations categorically rule out the possibility that random mutations (followed by selection) alone could be responsible for an evolutionary progression leading from the first simple protein molecule to man. The essence of his argument is that the time that such a progression would require, assuming a dependency on the mechanism of random mutations as proposed by Darwin, is very significantly longer than the time that was actually available for biological evolution on earth. The concept of random mutation is an essential prerequisite for evolution, but in itself it is not enough. If it is to retain its usefulness, Beer suggests, it must be qualified by assuming a process "that would impart a directional mechanism"(25) to the adaptive process. In other words, the randomness of mutations is not really "purely" random but is conditioned by the selective processes that are a function of the interaction of an organism and a particular environment. These actually bias mutations by reinforcing those organizations that are particularly survival worthy. The underlying randomness of mutation processes is therefore subject to a "higher level" control, which, by seeking to reinforce survival-worthy patterns, strongly conditions the direction (probabilities) that mutations might actually take. The process is self-regulating in that as it unfolds it changes conditional probabilities along its own path, the overall result being a gradual but "directed" increase in organization (with respect to more effective survival) and a great economy in the required time.

Barricelli, on the other hand, stresses another kind of difficulty(26) when he argues that the Darwinian theory is not sufficient to explain those major qualitative aspects of evolution that involve actual emergence of novelty and the formation of ever more complex organizations that are comparable to living organisms. The gist of Barricelli's argument is that Darwin's theory cannot explain the evolution of living organisms, and the great increase in variety that this evolution entails, if one starts with simple entities possessing only the capability to reproduce and mutate. More specifically, he argues that the evolutionary potential inherent in recombinational genes, the typical units of hereditary material, is quite limited in that a recombinational gene with n allelic states possesses a total variety which cannot exceed n different possibilities. Evolution is thus restricted to selecting the fittest from this total of n available possibilities (where n in this case is typically a small number). With this limitation in mind, Barricelli continues, "it is hard to visualize how such a self-reproducing element could, simply by mutation and selection, develop into a homo 'sapiens' or anything able to construct a homo sapiens even if allowance is made for the fact that the number of allelic states may be generally, or very often, underestimated."(27)

As Barricelli shows in his convincing experiments,(28) the difficulty can be removed if one assumes that in addition to reproduction, mutation, and selection, another principle is operative which tends to promote symbiosis and "co-operative" interaction between elementary self-reproducing entities. If such a principle of association is introduced, the limited number of allelic states in each self-reproducing entity no longer imposes the same limitation on possible variety, in that even if only two allelic states are assumed for each recombinational gene, the association of n such genes (where n in this case may be measured in several thousands) would produce a variety of 2^n possible states, thus dramatically increasing the total variety to which evolutionary selection can be applied.

This idea, which ties the notion of emergent novelty to the formation of symbiotic associations in which simple entities interact to form a new and more complex whole, is central to the so-called "symbiogenesis" theory which, according to Barricelli, seeks to explain the evolutionary process that led to the formation of cells as being a function of symbiotic associations between a number of virus-like organisms.(29) The crucial notion is that the products of such symbiotic interactions may in themselves retain the properties of self-reproduction and mutation while the concept of selection would now apply to the new organization which was formed by such an association. The important role of cooperative processes is thus brought to the fore. In fact, the lack of sufficient consideration of the role of cooperative processes in evolution has been a major source of criticism that has been leveled at Darwin's theory,(30) and since the turn of the present century various writers have emphasized the importance of integrative factors and cooperative interactions in organic as well as social evolution.(31)

From the viewpoint of effective survival, the critical point about the formation of such integrated associations is that when individual entities interact to form what may be called in effect a coalition, tasks may be jointly performed which could not have been accomplished by individual elements separately. Integrative factors which hold such coalitions together may be chemical in nature, or they may depend on communication processes and behavioral patterns of various complexities. Whichever the case, the net result translates into an effective increase in survival value that is achieved only by virtue of the new properties inherent in the coalition, which in itself may now be ragarded as a new single organism of higher complexity.(32)

The idea can be expressed in various ways. Firstly, from a functional viewpoint, new emergent properties of coalitions are the result of a synergetic effect, or a "super additive composition rule,"(33) where not only are such new properties unpredictable from the separate parts, but the related measure of the sum of the new whole is effectively larger than the sum of its parts. Similarly, from the viewpoint of regulation, the formation of a coalition accounts for a significant increase in variety (in the sense of producing a more effective regulator--as in Chapter 2). This increase can be viewed, in a sense, as being the result of a "hook up" of an element possessing a finite internal variety, to an "external" source. Finally, from an epistemological viewpoint, the notion of forming a coalition can be interpreted with respect to the idea of a single element facing an undecidable situation which can only be resolved by forming a new, more complex organization, containing sufficient variety, for which the situation is no longer undecidable.(34)

Coalition formation is thus an important evolutionary strategy and evidence of the integrative and cooperative processes that are implied is manifest in the various forms of systemic organizations that are found in nature. We have already mentioned the basic idea of "symbiogenesis theory" which sees the formation of cells as being the result of symbiotic association of more primitive elements. Much the same notion is applicable to various multicellular organizations. Indeed, Bonner(35) has stressed the essential role of cooperative processes in specific developmental stages of various simple organisms where the ability to aggregate results in a considerable survival advantage. The same principle, of an evolutionary stability which is manifest in "a continuous pressure towards integration,"(36) is evident in communities of animals and in human societies. The former are rendered stable by behavioral patterns which rely on the automatic operation of innate mechanisms of the type discussed by Lorenz and Tinbergen, while the latter depend on the externalized medium of a language and the framework of tradition and social conventions.

Eve-1, the model which will be described below, seeks to emphasize the role of cooperation and coalition formation in the evolutionary process.

3-2. Description of the Model

3-2.1. Design Objectives and Rationale

Eve-1 was conceived as a non-deterministic computer model of an abstract system which, when allowed to operate under pre-specified constraints, can be seen to exhibit evolutionary behavior. This behavior is exhibited by populations of simple automata the identity of which is not related to any particular "real" population. Attention was focused particularly on "cooperative" interaction between such automata, where "cooperation" was interpreted in its broadest sense. Thus, the emphasis was put upon the general role of coalition formation in evolution rather than on details concerning the working of mechanisms of reproduction and mutation. In the model, selective processes operate on specific coalitions, such selective processes being a function of a relation between attributes of given coalitions and particular environments.

In addition to the primary objective of mimicking evolutionary processes whereby complexity and survival efficiency of simple automata increase through the formation of coalitions, basic design criteria were related to some fundamental notions about evolution, a choice of an appropriate means to express them and a desire to achieve simplicity and clarity in presentation.

For example, Conrad and Pattee(37) point out that known evolutionary processes seem to operate on populations of individuals through a statistical selection process, although the specific differentiation mechanisms operate on individuals at a genetic level. It was intended to stress this fundamental notion and incorporate it in the structure of the model. Accordingly, it seemed logical to follow other investigators in selecting the general context of a population of randomly interacting individual entities defined as phenotypes, whose characteristics are derived from underlying genotypes according to a set of deterministic rules. This broad requirement is not sufficient, however, to define a specific type of system. Indeed, several types of abstractly defined systems possessing similar properties could be postulated, including topologically defined populations of interconnected nets such as those described by Kaufman(38) and Pask,(39) or patterns of numbers, such as described by Barricelli.(40)

Since the basic objective presented a field allowing a wide range of choice, further design criteria were introduced before a specific context was selected for implementation. Of these, the most important was the requirement that both the definition and the observed behavior of the model could be readily communicated and comprehended at an intuitive level even by someone who had no previous familiarity with it. This requirement, it was felt, could be satisfied by the use of a geometrically defined environment, various points of which could be occupied by localized entities so that an instantaneous "snapshot" of the system could be easily pictured on the computer printout. This type of approach was suggested by the work of other investigators, notably Pask,(41) but also Varela, Maturana, and Uribe.(42)

Basic entities in these models are typically defined as point-automata which can occupy the nodes of a planar grid constituting the "environment." The primary activities of these automata consist of movement from node to node and interaction with other automata. For the concept of evolution to be applicable in models utilizing this strategy it is necessary to allow for differentiation processes in the phenotypes of the automata as well as for a measure of fitness. The latter is usually incorporated by making survival conditioned upon the successful capture of some abstractly defined commodity, interpretable as "food," which is essential for the survival of the automata and which becomes available, by various means, in the environment. In some models, for example in Pask's,(43) the production of food is exogenous whereas in others, such as Conrad and Pattee's,(44) a closed system is defined in which food and the automata are "made" of the same substance the total amount of which is conserved during the operation of the model.

When confronted with simulations of this general class, one is likely to interpret the use of such concepts as movement, reproduction, food, gene, genotype, phenotype, species, etc., as though they stood directly for real physical systems, typically of a biological nature. It should be emphasized that this is not intended in Eve-1. The intuitively understood concepts mentioned above are used for the purpose of making it easy to follow the behavior of the model, but they should not be taken literally. In fact, several features of Eve-1, such as the rules for differentiation and the lack of decay by aging, were defined in ways which bear little similarity to the laws of biological systems.

In order to maximize the ease of using the model, a final objective was formulated: namely that as many of its features and functions as possible should be parametrized in a way which would allow changes in both environmental conditions and in the definition of phenotypes and their interactions, to be introduced at any time during an actual computer run. Unless a specific statement to the contrary is made, all parameters described in the following pages may be so defined. Clearly, by varying such parameters, practically an infinity of different specific models may be generated. Furthermore, small changes in the parameters may produce very significant discontinuous changes in the behavior of the model. To this date, only a few of the parameter combinations and only one of the environmental geometries that are possible in Eve-1 have been tried. The results will occupy the following sections of this chapter where a general description of the model is given and its observed behaviors are discussed. Exact specifications, in an abbreviated form, and information on the software design and the hardware used may be found in Appendix A.

3-2.2. Eve-1: General Overview

Following the considerations described in the previous section, a specific model was formulated and implemented on a digital computer. The context of the model is that of an abstract eco-system in which simple automata of several different species can move about, compete for "food" which is present in their environment, reproduce, and combine with other automata to produce automata of new and more complex species. The system is an open one in the sense that food becomes available in the environment through an exogenous process, and unsuccessful automata which die of "hunger" disappear completely without having any of their fabric return to the system in any way. The model was deliberately defined in this way so that its adaptive and evolutionary behavior could be studied with a variety of food availability patterns which are exogenously defined and modified by the investigator. In this way, differences in the evolution of the system may be studied under various conditions, for example under conditions where food appears in a uniform distribution, in localized high concentrations, etc.

Each automaton has the capacity to "see" food particles as well as other automata in its vicinity, and it can "move" according to what it sees. These capabilities of sensing and movement are considered to be the "primary characteristics" of the automata, and it is with respect to these characteristics that various species essentially differ. (There are also differences among species with respect to metabolic requirements and other such "secondary characteristics.")

Food appears in the model in the form of discrete particles associated with different "food values." When an automaton moves to a node containing a food particle, it may "eat" that particle, in which case its "food store" is incremented by the particle's food value and the particle is removed from the environment. The food store of every automaton is decremented each time step by an amount (the "metabolic rate") which depends on the species to which the automaton belongs.

If the food store of an automaton becomes zero or negative, the automaton dies; if it reaches or surpasses a particular threshold value, the automaton reproduces.

Finally, a way is provided for "hungry" automata to combine and form automata of new species. Survival in the system thus clearly depends on the ability of an automaton to capture enough food to cover its metabolic cost. Its sensing and movement characteristics determine this ability.

Each species is defined in terms of an abstractly conceived "genotype" consisting of two small integers which are thought of as "genes." The "phenotype" of each species (consisting of its primary and secondary characteristics) is derived from its genotype according to a set of rules which may be externally changed between or during simulations. The processes responsible for the introduction of new variety (new species) into the system operate at the genetic level whereas the processes responsible for the survival of a species operate at the population level of the total system. The effects of both are non-deterministic when seen macroscopically, since they are affected by random variables in the environment and in the actions and interactions of the automata themselves. (Microscopically, however, random actions are taken only in undecidable situations.)

When observing and analyzing the operation of the model, we may speak of the "fitness" of a species as manifested by its survival when steady state is reached. In addition, it is possible to think of the "efficiency" of the total system of all automata as manifested by their ability to keep the amount of free food in the environment at a minimum. This concept of efficiency is similar in scope to the concept of "utilization ratio" that is used in the model of Conrad and Pattee.(45) It will be discussed more fully in sections 3-4.2 and 3-4.3 below.

3-2.3. The Environment

a. Topology and Geometry

In Eve-1, the environment consists of the nodes of a planar rectangular grid the size of which may be varied. (Most of the computer runs were made on a square grid of 30 x 30 = 900 nodes, although sizes up to 100 x 100 = 10,000 nodes are possible in the same computing environment.) Each node of the grid is assumed to be "linked" to all of its eight immediate neighbors, except that nodes on the boundary are linked to three other nodes (corners) or five other nodes (edge). Although the grid is depicted for simplicity as a geometrically uniform one (see Figure 7), only its topology (connectivity) is of interest in this model. The distance between two nodes of the grid is defined in terms of the number of links in the shortest path between them. Thus, when the grid is drawn with uniform geometrical spacing, the locus of all nodes which are equidistant from a given node P is the perimeter of a square (not a circle) centered at P. Figure 7 shows a typical portion of the 30 x 30 grid with all links between nodes drawn. The heavy dots indicate the locus of all nodes at distance 2 from P.

Each node of the grid may be specified as "accessible" or "inaccessible" for a particular computer run so that the

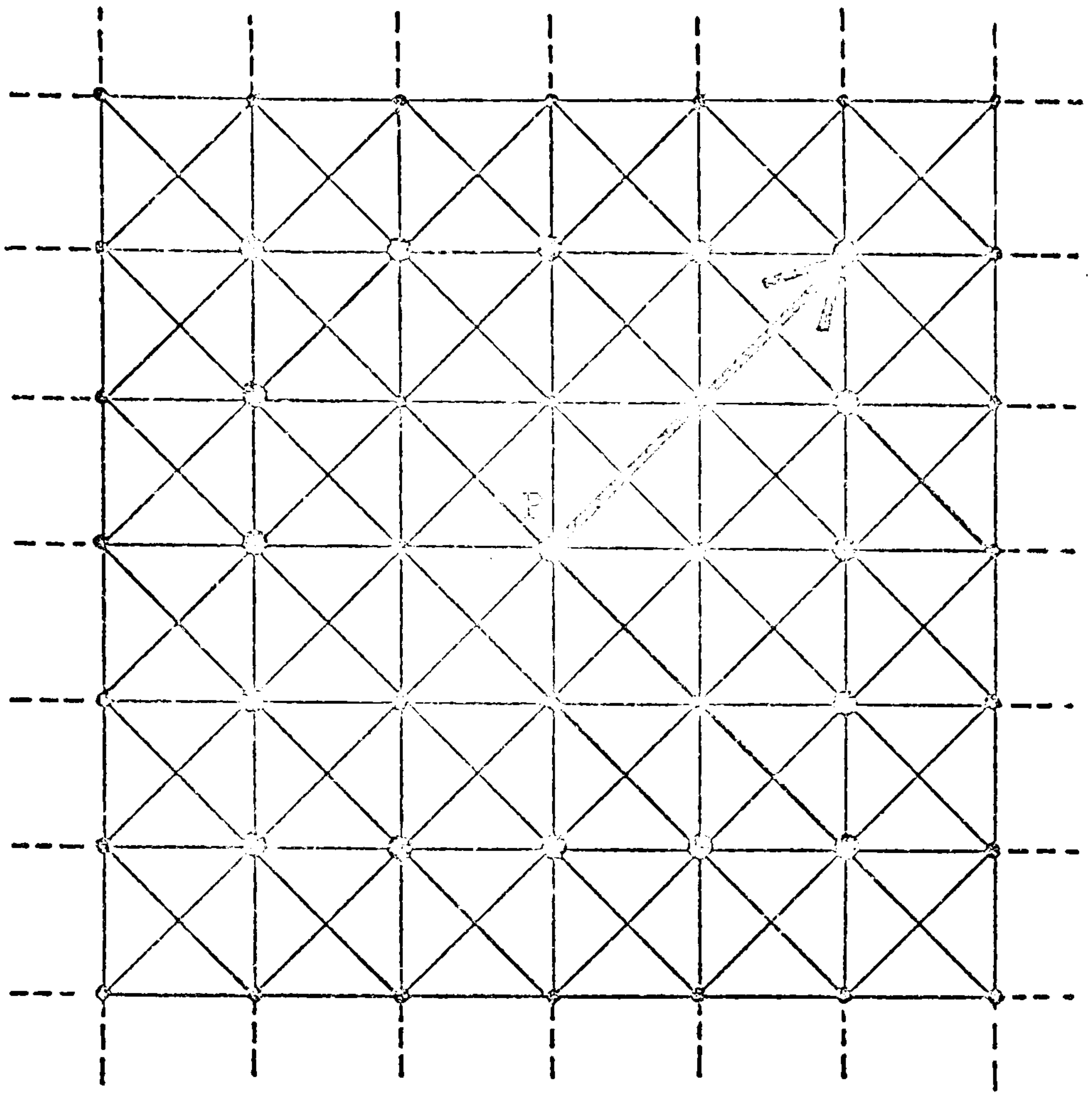


Figure 7: A segment of the environment where nodes are indicated by dots. Heavy dots represent the locus of all nodes at distance 2 from node P.

actual shape of the environment may be arbitrarily defined to include continuous fields, mazes, barriers, etc. Every accessible node (hereafter, reference to a node will imply an accessible node unless otherwise noted) may contain no more than one automaton and one food particle at any given time step, so that a "snapshot" printout is able to show all automata that are occupying the grid at a given instant.

b. Food

Food is introduced into the environment (exogenously) in the form of food particles, each of which appears and remains on one node until eaten by an automaton. Each food particle has a certain "food value" which remains constant until the particle is eaten. Each node may contain at most one food particle (in addition to one automaton). A certain maximum number of food particles is introduced into the environment every time step on randomly selected nodes which (a) are accessible, and (b) have no food particle already on them. This is done in a number of trials in each of which a node is selected randomly from all nodes and tested for accessibility and food content. If the node is accessible and contains no food particle already, a new particle is introduced there. The process ends when the maximum number of particles per step (NFOOD) has been placed or a maximum number of trials (NFTRY) has been reached. In this way, an increase in the concentration of food particles in the environment leads to a statistical decrease in the rate of introduction of new food. This rate, however, does not explicitly depend on the number or concentration of automata.

The food value of each particle is set at the time of its generation to a random value in a prespecified range (FVMIN, FVMAX), and it is measured in the same units as the food store levels and metabolic requirements of the automata (see below). In some of the simulations, FVMIN was set equal to FVMAX so that all food particles had equal values. In all cases, an automaton can sense and eat only food particles whose value is greater than or equal to the amount of food it needs per time step in order to survive (its metabolic rate). This particular constraint provides for the generation of ecological niches and may induce symbiotic behavior among species. (If food particles of a particular value are never eaten, then they will gradually accumulate and fill the environment so that other kinds of particles will find no free space to "grow.")

Collectively, the parameters NFOOD, NFTRY, FVMIN, and FVMAX are referred to as "the food availability pattern" since they control the number and value of the food particles introduced into the system. In certain runs, a special change was made in the program so that parts of the environment were accessible to automata but no food could be generated there. This, however, was not introduced as a permanent feature in the program.

3-2.4. The Automata

a. Species Characteristics: The Phenotypes

Automata are defined as dimensionless entities each of which may occupy one grid node in any given time step. At most one automaton may be present on a node, and if this happens the node is "occupied." Automata are able to sense the environment in their vicinity and to move from node to node according to rules which will be described below. There are 24 different possible types (species) of automata, and each species is defined by a genotype. The behavioral characteristics of a species (its phenotype) are a function of its genotype. (The way in which one relates to the other is described in section 3-2.4.d.) The automata "live"and function in a stream of discrete time steps. Although the program remembers each automaton's age, none of the characteristics of the automata are affected by aging.

The two primary characteristics of species have to do with the extent of their ability to sense the environment and to move in it. The sensing characteristic (which may be thought of as "vision") is defined as the value of the "radius of sensing" (RS), and the movement characteristic as the value of the "radius of movement" (RM) for each species in each time step. RM and RS are small integers, different for each species, which define the distance from an automaton, expressed in numbers of nodes, within which it can "see" and "move" each time step. Since automata can see and move in all eight possible directions on the grid, these radii actually delimit square regions of vision and possible movement around each automaton at each time step. If an automaton sees a food particle the value of which is at least as great as the automaton's metabolic rate, then it moves towards that particle and, upon reaching it, eats it. If an automaton sees no food particles in a particular time step, then its movement is influenced by whether it sees other automata. If none are within sight range, it moves randomly as far as it can. If, on the other hand, it detects the presence of other automata, it will either move towards its closest neighbor seeking coalition (if it is hungry) or away from it (if well fed). Note that the radius of movement per time step is equivalent to a measure of speed.

Some species are able to see further than they can move in one step (RS>RM), and thus may home in on a target (e.g., a food particle) in a sequence of time steps. Others can move further than they can see (RS<RM), and these will in fact move about even if they cannot see a target within their radius of vision. As may be seen in Figure 7, a square region with radius R contains $(2R+1)^2$ nodes. Thus an automaton with RS = 1 can "see" 9 nodes whereas one with RS = 5 can see 121 nodes at any given time.

In addition to the primary characteristics of range of vision and movement, species have secondary characteristics having to do with their metabolic requirements, reproduction, etc. These secondary characteristics are described further below.

b. Genetic Definition: The Genotypes

Each species has two "genes," corresponding to the two primary characteristics: a sensing gene (G_s) and a movement gene (G_m). Each gene can have an integer value between 0 and 4. The genotype of a species is defined by the values of its two genes, and it may therefore be represented by the ordered pair (G_s, G_m). The translation of the gene values into the corresponding species characteristics depends on the currently prevailing rules for generating a phenotype from a genotype. These rules may vary with different runs in a manner which will be described in section 3-2.4.d below.

Since each gene may have one of five values (0 to 4), there can be 5 x 5 = 25 possible genotypes. Of these, (0, 0) is referred to as "null" and is not allowed to exist. Thus, the actual number of possible genotypes is 24. The reason for this limitation is twofold: (a) the requirement of easily readable printed output could be easily fulfilled by representing each species by one alphabetical character (a - x are used); and (b) the same requirement is also served by the fact that the 24 species (plus the null species) can be tabulated in a 5 x 5 "species matrix" in which the sensing gene's value increases in the horizontal direction and the movement gene's value increases in the vertical direction. Such a tabulation showing the one-letter label of each species is shown in Figure 8.

G_s value →

		0	1	2	3	4
G_m value ↓	0		A	D	I	P
	1	B	C	F	K	R
	2	E	G	H	M	T
	3	J	L	N	O	V
	4	Q	S	U	W	X

Figure 8: Species matrix showing species lables tabulated by gene values.

As may be seen from this matrix, species A has genotype (1, 0), species T has genotype (4, 2), etc. (The null species has genotype (0, 0) and no label; no automata of this species are ever generated.) The gene values are not necessarily the same as the corresponding radii of sensing and movement (for further discussion see section 3-2.4.d below).

For the purpose of discussion, a species is referred to as "advanced" if the numerical sum of its two genes' values is high. X is the most advanced species ($G_s + G_m = 8$), A and

B are the least advanced ($G_s + G_m = 1$), W is more advanced than N, etc. In the species matrix described by the table of Figure 8, the level of advancement increases from the top left to the bottom right, and the matrix is symmetric about its main diagonal with respect to advancement level. The assignment of letter labels to species, though formally arbitrary, has been made so that the relative order of the letters in the alphabet roughly corresponds to relative advancement levels, a feature aimed at improved readability of the printed output.

Note that the level of advancement is not enough to identify a species, nor is it to be interpreted as an absolute measure of fitness. The latter is a qualitative attribute of the phenotype which is relative to current environmental conditions but is not "internally" defined in the model. Although the level of advancement itself plays no formal role in the model, it was in practice often used as a guide in assigning metabolic costs and other metabolism-related characteristics, to each species for specific runs. In most cases, this could be interpreted as meaning that (a) a unit of vision capability is metabolically equal to a unit of movement capability, and (b) the total metabolic cost of an automaton depends on the sum of these two capabilities plus a fixed cost. In this regard it should be added that the level of advancement is meaningful only if the relative sizes of gene values match the relative values of the corresponding specie's characteristics (movement and sight) in particular assignments.

The structure, number and properties of genotypes are fixed in Eve-1 and they cannot be changed for different simulations. The ways in which phenotypes are derived from genotypes, however, are easily controllable. These may be changed between or during specific simulations to produce an essentially infinite variety of behaviorally different species (although no more than 24 of them may exist at one time).

c. Generation of New Automata: Reproduction and Coalition Formation

There are two ways for new automata to be generated. In the first, defined as "reproduction," an automaton whose food store level has increased beyond a certain threshold (REPROL), gives "birth" parthenogenetically to another automaton of the same species. (The new automaton receives an "initial food store" which is subtracted from the parent.) In the second, defined as "coalition formation," two automata, of the same or of different species, may combine to form one or two new automata which in general are of different species. The exact rules for coalition formation are given in Appendix A, but the following will provide a general description of the event.

When the food store of an automaton has been depleted beyond a certain level (COMBL), a fact indicating that the automaton has been unsuccessful in its recent attempts to capture food, then it will seek to approach and combine with any other automaton it can see. If it manages to approach another automaton, and if this second automaton is also "hungry" in the same sense of having had its food store level depleted to a critical level, then the two will combine by numerically adding their gene values, to form a new automaton of a more advanced species. If this addition of the values for either gene yields a number g greater than 4 (which is the maximum allowed), then a second new automaton is generated. The first of the two new automata will then receive a value of 4 for each of the genes that caused an addition overflow, and the second will receive the surplus value (g-4). With this combination rule, the sum of the values of all sensing and movement genes of the population is conserved under coalition formation.

The automata generated by a coalition formation have "zero" age, but their food stores add up to the sum of the food stores of the automata that combined. Automata whose age is less than a specified number (MCOAGE) cannot form new coalitions, a rule which ensures that automatic recombination will not occur immediately after the formation of a new coalition for which food store levels are initially low. Each specific coalition formation may be written as a production where the symbol "→" shows the direction of the coalition event. Examples of such events written in this way in both the genotype and the sumbolic (letter) notations are the following (for clarity refer also to Figure 8):

	GENOTYPE NOTATION	SYMBOLIC NOTATION
(1)	$(1,0) + (0,1) \rightarrow (1,1)$	$A + B \rightarrow C$
(2)	$(1,1) + (1,2) \rightarrow (2,3)$	$C + G \rightarrow N$
(3)	$(2,2) + (2,3) \rightarrow (4,4) + (0,1)$	$H + N \rightarrow X + B$
(4)	$(4,4) + (1,2) \rightarrow (4,4) + (1,2)$	$X + G \rightarrow X + G$

Note that in each coalition formation the first new automaton produces is in general more advanced than either of the two that formed the coalition. The second new one, however, if a second one is produced, is less advanced than either of them. Therefore, coalition formation introduces variety into the population by continuously generating both more and less advanced species, although the latter at a frequency lower than the former. This condition is peculiar to the model and is a result of the specific constraint which imposes an upper limit on the possible levels of genotypes' values.

Because of this very same constraint, certain coalition events produce no new variety. For example, a coalition of any species with X will yield the same two species. This is due to the fact that the genotype of X (4,4) has both its values already saturated. In general, a coalition will produce no variety in one gene if either of the two species combining has a value of 0 or 4 for that gene. If this happens for <u>both</u> genes in a certain coalition event, and if the event is such that two automata are produced, then these will be identical to the original automata forming the coalition. Clearly the great majority of possible coalition events do not belong to this class.

Thus, in the model, coalition formation is responsible for the introduction of variety into the population, whereas reproduction is responsible for numerical multiplication within each successful species. In this way the evolutionary and the ecological behavior of the total system may be studied and controlled separately. The easiest way to achieve this control is by changing the food store thresholds required for reproduction or coalition formation in some or all of the species.

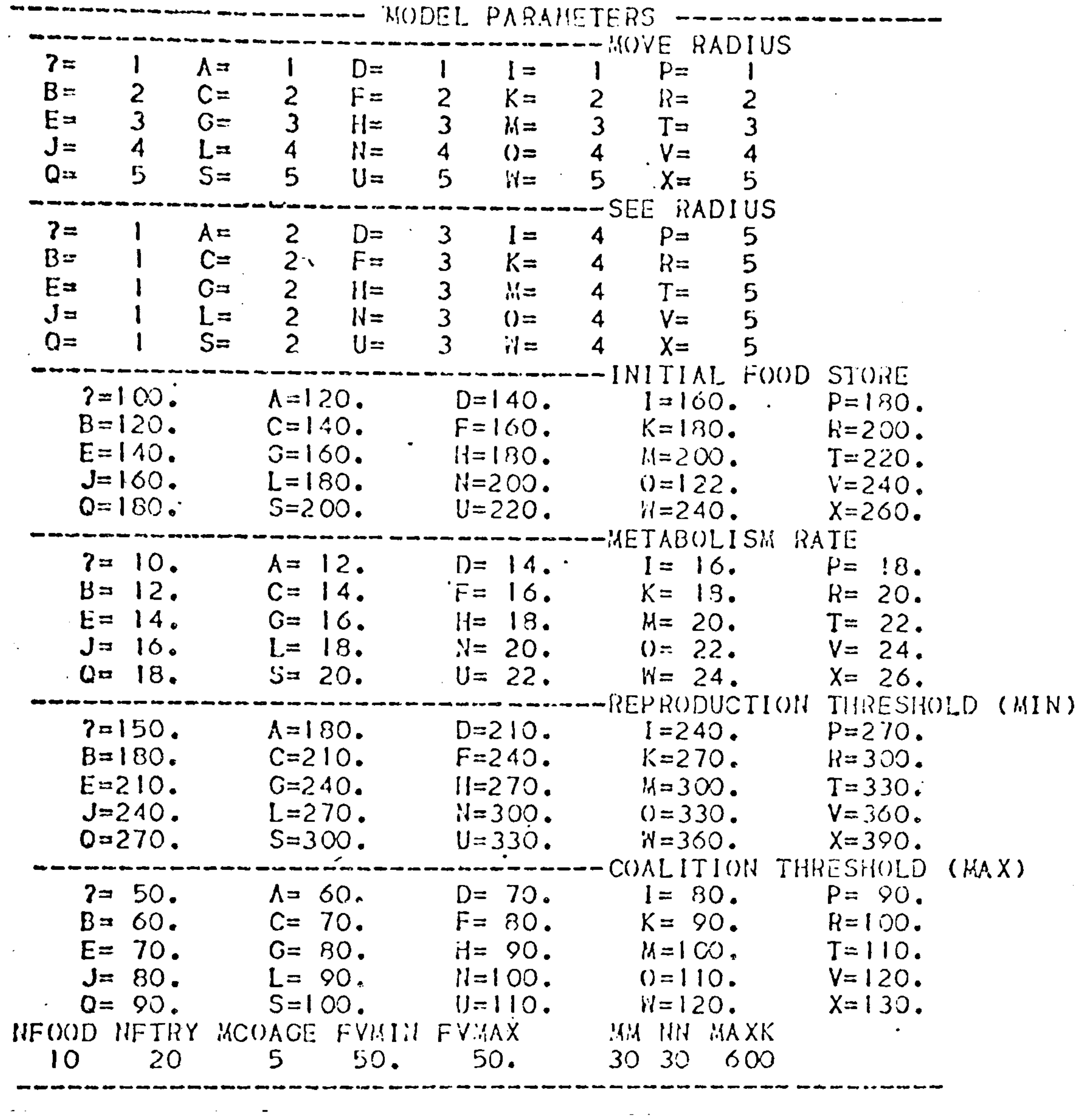
d. Derivation of Phenotypes from Genotypes

The phenotype of each species is the set of its six characteristics, all of which are numerically defined. These include: sensing radius, movement radius, initial food store, metabolic rate, (minimum) food store level required for reproduction, and (maximum) food store level required for coalition formation. The first two of these are considered as primary characteristics, while the remaining four are secondary.

As previously mentioned, the characteristics of a species are a function of its genotype, i.e., its two gene values. Although it would have been possible to define algebraic formulas for the derivation of the characteristic values from the gene values, the method used in Eve-1 for this derivation is a series of table look-ups. This is made conceptually (and functionally) simpler by the fact that all species may be tabulated in a 5 x 5 matrix (as in Figure 8 above) with respect to any of their characteristics. Thus, the program maintains six such 5 x 5 matrices at all times, one for each of the species characteristics. To find the metabolism rate of species (G_s, G_m), the corresponding matrix is simply indexed with the numbers G_s G_m. (The structured form of these six matrices enables a table look-up to be performed without spending any time in a search--for further details, see Appendix A.)

The content of the six characteristics matrices are an input to the model and may be modified at any time during a simulation. These six matrices, together with the geometry of the environment and the food availability pattern (sections 3-2.3.a and 3-2.3.b respectively), completely specify a particular "universe." Different simulations may be run on the same universe by changing the initial configuration of automata and/or by changing the initialization of the random number generating subroutine of the program. Figure 9 below shows a complete specification of a typical universe (excluding the environmental geometry). The behavior of the model with different such specifications is discussed in Section 3-3.

From the species label matrix in Figure 8, we see that species R, for example, has the genotype (4,1). Using these gene values we can find (see Figure 9) that under the specifications of that particular universe, the sensing radius of species R is 5, its movement radius is 2, its metabolism rate is 20, its initial food store is 200, its reproduction threshold is 300, and its coalition formation



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------------------------- MODEL PARAMETERS ----------------
----------------------------------------MOVE RADIUS
 ?=   1   A=   1   D=   1   I=   1   P=   1
 B=   2   C=   2   F=   2   K=   2   R=   2
 E=   3   G=   3   H=   3   M=   3   T=   3
 J=   4   L=   4   N=   4   O=   4   V=   4
 Q=   5   S=   5   U=   5   W=   5   X=   5
----------------------------------------SEE RADIUS
 ?=   1   A=   2   D=   3   I=   4   P=   5
 B=   1   C=   2   F=   3   K=   4   R=   5
 E=   1   G=   2   H=   3   M=   4   T=   5
 J=   1   L=   2   N=   3   O=   4   V=   5
 Q=   1   S=   2   U=   3   W=   4   X=   5
----------------------------------------INITIAL FOOD STORE
    ?=100.      A=120.      D=140.      I=160.      P=180.
    B=120.      C=140.      F=160.      K=180.      R=200.
    E=140.      G=160.      H=180.      M=200.      T=220.
    J=160.      L=180.      N=200.      O=122.      V=240.
    Q=180.      S=200.      U=220.      W=240.      X=260.
----------------------------------------METABOLISM RATE
    ?= 10.      A= 12.      D= 14.      I= 16.      P= 18.
    B= 12.      C= 14.      F= 16.      K= 18.      R= 20.
    E= 14.      G= 16.      H= 18.      M= 20.      T= 22.
    J= 16.      L= 18.      N= 20.      O= 22.      V= 24.
    Q= 18.      S= 20.      U= 22.      W= 24.      X= 26.
----------------------------------------REPRODUCTION THRESHOLD (MIN)
    ?=150.      A=180.      D=210.      I=240.      P=270.
    B=180.      C=210.      F=240.      K=270.      R=300.
    E=210.      G=240.      H=270.      M=300.      T=330.
    J=240.      L=270.      N=300.      O=330.      V=360.
    Q=270.      S=300.      U=330.      W=360.      X=390.
----------------------------------------COALITION THRESHOLD (MAX)
    ?= 50.      A= 60.      D= 70.      I= 80.      P= 90.
    B= 60.      C= 70.      F= 80.      K= 90.      R=100.
    E= 70.      G= 80.      H= 90.      M=100.      T=110.
    J= 80.      L= 90.      N=100.      O=110.      V=120.
    Q= 90.      S=100.      U=110.      W=120.      X=130.
NFOOD NFTRY MCOAGE FVMIN FVMAX      MM NN MAXK
 10    20    5     50.    50.       30 30  600
-------------------------------------------------------------
```

Figure 9: Model parameters specifying a typical Universe. (See also Appendix A).

threshold is 100. Although the secondary characteristics were varied somewhat in different simulations (see section 3-3), vision and movement radii for different species were kept at the values shown in Figure 9 for all runs. Each of these values was arrived at (quite arbitrarily) by adding 1 to the corresponding gene value for each species. Thus the value of the radii of movement and vision ranged between 1 and 5 for different species. As previously mentioned, these values correspond to square regions containing 9 to 121 nodes (for radius values of 1 and 5 respectively). Intermediate radius values correspond to regions with intermediate numbers of nodes.

3-2.5. Implementation of Parallel and Random Events in Eve-1

Some specific information on the computer program is included in Appendix A. In the present section are discussed only those aspects of the implementation which affect the stochastic operation of the model.

Models like Eve-1 are usually defined so that their various processes are assumed to occur simultaneously, i.e., in parallel. Implementation on a digital computer such as those available today, however, is of necessity serial. Since Eve-1 is not meant to be a model of a real-world parallel system, this is not, in principle, seen as a limitation. Nevertheless, several steps have been taken to minimize the effect of serial computation on the behavior of the model so that the observed events could be explained more easily. These steps include the following:

(a) A double-array scheme (see also Appendix A) allows all actions in time step t_i, having to do with positions of automata and food particles, to be made on the basis of exactly the same information, namely the state of the universe at the end of time step t_i-1. The two sets of arrays are referred to as "old" (for t_i-1) and "new" (for t_i), and they exchange their names (rather than their content, which might be more expensive) at the end of the processing of each time step. It should also be noted that, since at most one automaton may occupy one node, automata can only move to nodes which are free both in the "new" and "old" arrays. This means, in fact, that the same node may not be occupied by two different automata in two consecutive time steps.

(b) The processing of automata in each time step is done in four distinct passes, each of which involves a scan of the list of all automata. In the first pass, automata age and metabolize, and those whose food store becomes negative die and are removed from the system. In the second pass, automata sense their environment, move, and feed if they have reached a food particle. In the third pass, automata which are ready to reproduce are allowed to do so. Finally, in the fourth pass, coalitions are formed between pairs of automata which are adjacent and "willing" to combine (i.e., "hungry"). Abbreviated flow charts for these four passes can be found in Appendix A.

(c) Although the four-pass processing method goes a long way towards improving the parallel character of the model, an important problem of serial processing still remains within the second pass: when two or more automata are within vision and movement range of a food particle, the one that gets it is the one that is processed first by the program. To eliminate this bias in favor of specific automata in the second pass, Eve-1 scans the list of automata in alternate directions (top/down, bottom/up) in consecutive time steps. Thus, the bias works alternately in favor and against a specific automaton, and the statistical result is that no automata are favored over a long sequence of steps. (The order of scanning also affects the third and fourth passes to a certain extent, but there the effect is less systematic and was not felt capable of altering the statistical behavior of the model.)

Besides the order of scanning the automata in each of the four passes each time step, there are other features of the implementation of specific individual events that could create unwanted systematic trends. When an automaton reproduces, for example, a node immediately adjacent to it must be found which is free in both the "old" and "new" arrays. In order to find such a node, the program first selects one of the eight adjacent nodes at random, then looks at the remaining seven (if necessary) in a sequence that depends on which the first one was. (If no free nodes are found, the reproduction does not take place because of crowding.) This procedure makes certain that no preferred geometrical direction of reproduction will exist. Similarly randomized searches are also used in other cases when the neighborhood of a node is searched for something (for example, during coalition formation events in the fourth pass).

The random number generator used in Eve-1 will reproduce the same sequence of random numbers if initialized in the same way. This feature proved useful, since one run could be repeated with different output options when increased detail of the operation was desired in the printout.

3-2.6. Using the Model

a. Inputs

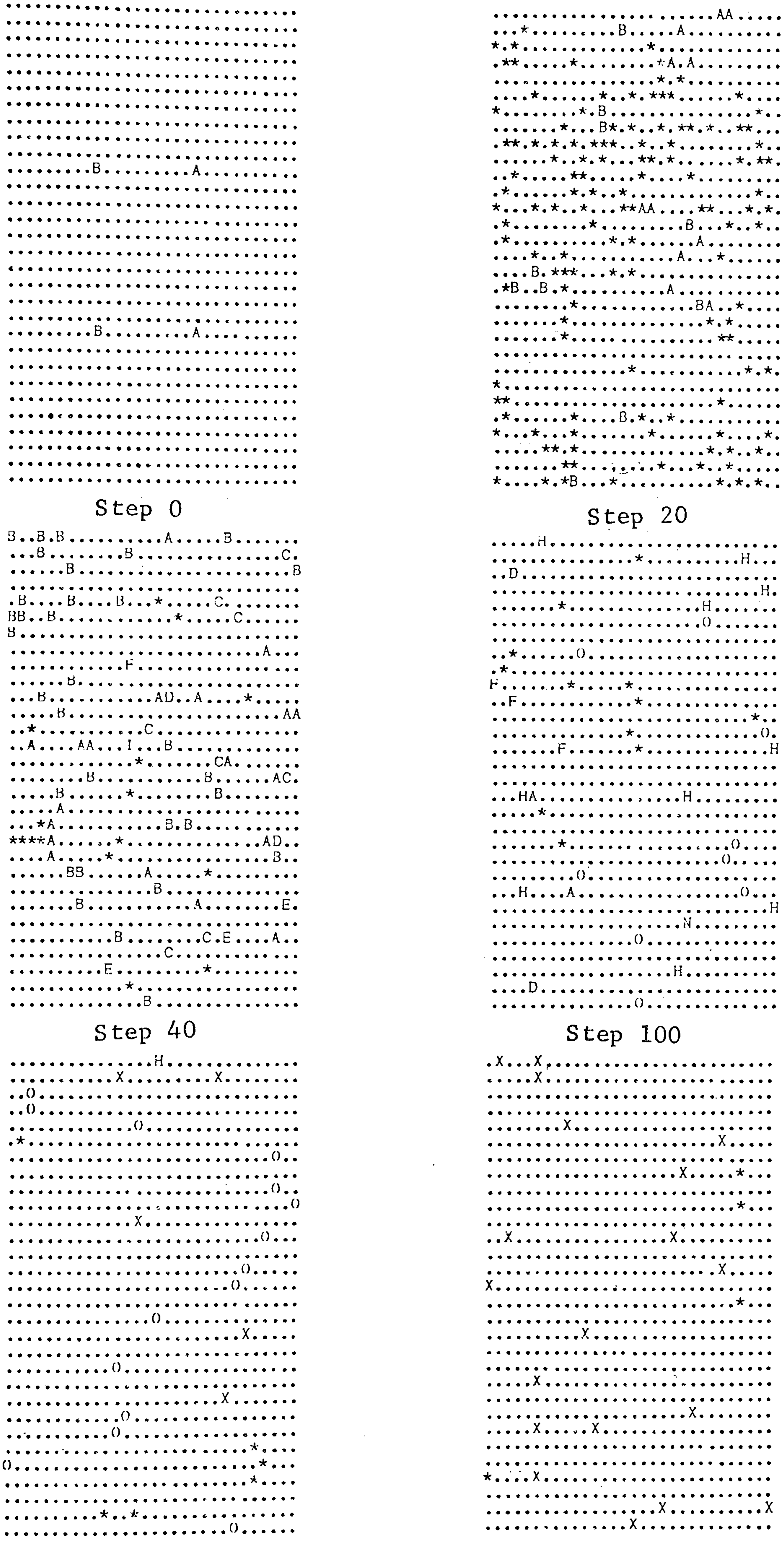
Although all simulations to date have been made in an off-line mode, the program has been written so that it can be run interactively. Accordingly, input to the program is made through one-line commands, each of which consists of a command name and one or more arguments. For example, the command FVAL 10 40 sets the values of FVMIN and FVMAX (see section 5-2.3.b) to 10 and 40 respectively, whereas the command GO 400 causes the simulation to proceed for 400 steps. When running off-line, sequences of such commands are written which then effectively constitute higher level programs controlling the execution of Eve-1. The program prints each command it receives on the printout followed by any further output that the execution of that command may produce.

b. Outputs

One of the commands that the program accepts causes the printout of the complete current specifications of the model, i.e., the kind of information contained in Figure 9 of section 3-2.4.d. In addition, other commands set parameters and "logical switches" which control the type of information printed during an actual simulation. Each type of information printout is associated with a variable frequency, so that it is only produced whenever a certain number of time steps has elapsed.

One type of printed output that has already been mentioned is the "snapshot" of the universe, showing the environment with the automata and food particles on it. The automata are represented with the one-letter labels shown in the species label matrix (see page 103), the food particles are represented as asterisks, and nodes with neither an automaton nor a food particle on them are represented as dots. When a node contains both an automaton and a food particle (This can be the case at the end of a time step only if the particle is too small to be eaten by the particular automaton, or, if the automaton was created in that time step.), then only the automaton is shown. Figure 10 below shows "snapshots" of time step 0, 20, 40, 100, 160, and 400 of a typical simulation. (Step 0 corresponds to the initial configuration, defined by a sequence of input commands.) The model parameters in this run had values corresponding to those shown in Figure 9.

Although the snapshot printouts are useful in gaining an intuitive understanding of the model and in visually detecting spatially differentiated patterns (see section 3-3.2.e), most of the data analysis was done using primarily printed "vital statistics." This printout starts with a line giving the current time step number (STEP), total number of automata (AUTOM), total number of food particles (FOODP), total number of automata created since step 0 (CREATED), total number of coalition formations since step 0 (COMBINED), and total number of "hunger deaths" since step 0 (DIED). This data is followed by a printout of a 5 x 5 species matrix showing the population of each species. (This matrix is similar



Step 0

Step 20

Step 40

Step 100

Step 160

Step 400

Figure 10: A typical run made with the specifications of Figure 3 showing snapshots of the universe at time steps 0, 20, 40, 100, 160 and 400.

```
STEP   AUTOM    FOODP   CREATED   COMBINED   DIED
 0        4       0        4          0        0   %
-------------------------------------SPECIES POPULATIONS
      RS=1  RS=2  RS=3  RS=4  RS=5
RM=1    0     2     0     0     0           ?    A    D    I    P
RM=2    2     0     0     0     0           B    C    F    K    R
RM=3    0     0     0     0     0           E    G    H    M    T
RM=4    0     0     0     0     0           J    L    N    O    V
RM=5    0     0     0     0     0           Q    S    U    W    X

STEP   AUTOM    FOODP   CREATED   COMBINED   DIED
 20      21      130      22          0        1   %
-------------------------------------SPECIES POPULATIONS
      RS=1  RS=2  RS=3  RS=4  RS=5
RM=1    0    11     0     0     0           ?    A    D    I    P
RM=2   10     0     0     0     0           B    C    F    K    R
RM=3    0     0     0     0     0           E    G    H    M    T
RM=4    0     0     0     0     0           J    L    N    O    V
RM=5    0     0     0     0     0           Q    S    U    W    X

STEP   AUTOM    FOODP   CREATED   COMBINED   DIED
 40      66       16      91         13       25   %
-------------------------------------SPECIES POPULATIONS
      RS=1  RS=2  RS=3  RS=4  RS=5
RM=1    0    19     2     1     0           ?    A    D    I    P
RM=2   32     8     1     0     0           B    C    F    K    R
RM=3    3     0     0     0     0           E    G    H    M    T
RM=4    0     0     0     0     0           J    L    N    O    V
RM=5    0     0     0     0     0           Q    S    U    W    X

STEP   AUTOM    FOODP   CREATED   COMBINED   DIED
100      27       12     153         64      126   %
-------------------------------------SPECIES POPULATIONS
      RS=1  RS=2  RS=3  RS=4  RS=5
RM=1    0     2     2     0     0           ?    A    D    I    P
RM=2    0     0     3     0     0           B    C    F    K    R
RM=3    0     0    10     0     0           E    G    H    M    T
RM=4    0     0     1     9     0           J    L    N    O    V
RM=5    0     0     0     0     0           Q    S    U    W    X

STEP   AUTOM    FOODP   CREATED   COMBINED   DIED
160      21        6     181         30      160   %
-------------------------------------SPECIES POPULATIONS
      RS=1  RS=2  RS=3  RS=4  RS=5
RM=1    0     0     0     0     0           ?    A    D    I    P
RM=2    0     0     0     0     0           B    C    F    K    R
RM=3    0     0     1     0     0           E    G    H    M    T
RM=4    0     0     0    15     0           J    L    N    O    V
RM=5    0     0     0     0     5           Q    S    U    W    X

STEP   AUTOM    FOODP   CREATED   COMBINED   DIED
400      19        4     253        123      234   %
-------------------------------------SPECIES POPULATIONS
      RS=1  RS=2  RS=3  RS=4  RS=5
RM=1    0     0     0     0     0           ?    A    D    I    P
RM=2    0     0     0     0     0           B    C    F    K    R
RM=3    0     0     0     0     0           E    G    H    M    T
RM=4    0     0     0     0     0           J    L    N    O    V
RM=5    0     0     0     0    19           Q    S    U    W    X
```

Figure 11: Vital statistics corresponding to the snapshots of Figure 10.

to those shown in Figure 8, except that its columns and rows are labeled by sensing and movement radius values rather than by the corresponding gene values.) Figure 11 below shows the vital statistic printouts corresponding to the snapshots of Figure 10.

The program also generates on the printout sheet rough plots of species populations and a variety of other quantities as they change in time. Figure 12 shows typical plots representing the species populations (bottom) and the sum of the values of all free (uncaptured) food particles in the environment for the same run depicted in Figures 10 and 11.

Finally, a specific simulation or portion of a simulation may be analyzed in detail by asking the program to print out a complete record of every single event. This, of course, can generate enormous volumes of printout, and was useful mainly for program verification in the beginning. In this mode, each food particle generation, automata reproduction, coalition formation, and hunger death is identified by location on the grid and all other pertinent information. Of particular interest is the printout of coalition formations, as it is given in the production format mentioned earlier (for example: $C + A \rightarrow F$, $V + F \rightarrow X + D$, etc.).

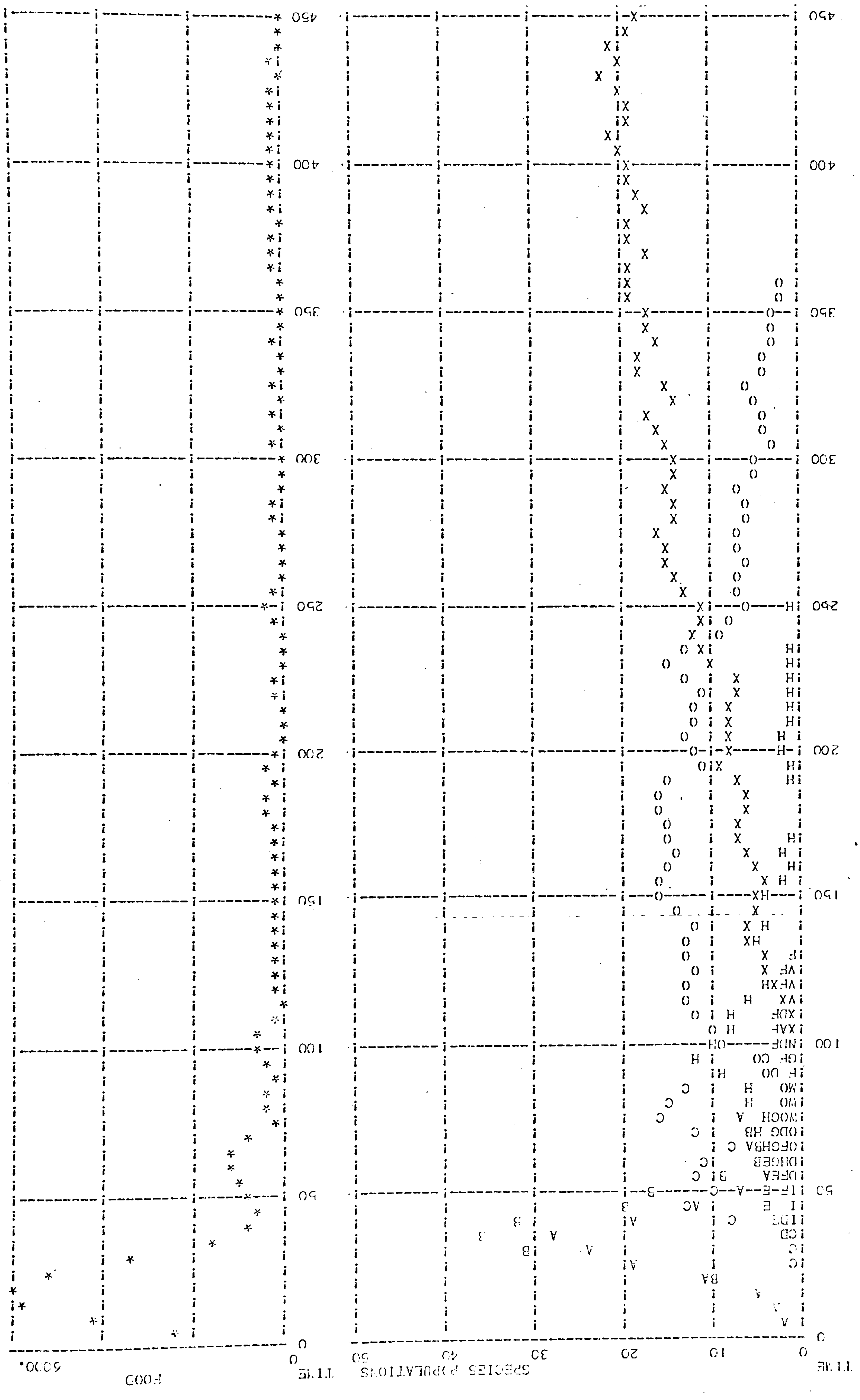


Figure 12: Time plots showing species populations and food particles in the simulation shown in Figures 10 and 11.

3-3. Some Results of Experimenting with Eve-1

3-3.1. Introductory Remarks on the Behavior of the Model

On the most general level an important result after over a hundred computer runs of Eve-1 has to do with the fact that non-trivial events in both ecosystem behavior and evolutionary behavior were observed in all cases. Although both the species characteristics and the environmental parameters could be changed in different runs, it was decided to experiment primarily with changes in the environment, specifically in the food availability pattern. Thus, in most of the runs to date, the species characteristics were kept unchanged (with a few exceptions) whereas the number and sizes of the food particles introduced into the environment were changed in several different ways. These changes, as is described below, resulted in significant variations in the behavior of the automata populations. The only species characteristic that was varied significantly in some runs was the metabolic rate, and the reason, as well as results of this change, are explained in subsequent sections. On the other hand, the primary characteristics (vision and movement radius) of each species were the same in all runs, and all secondary characteristics matrices were always symmetric about the main diagonal (i.e., vision and movement were assumed to have equal metabolic requirements). This equality in the internal treatment of vision and movement assured that the prevalence of one or the other in different environmental conditions was a consequence only of their relative performance and not in any way influenced by a preprogrammed bias.

In every run, an initial state of the system was externally defined before the operation of the model was started. The initial states always consisted only of species A and B, which may be considered as building blocks since they are the least advanced species and since all other species can emerge from them through various coalition formations. Most runs were started with no food present in the environment--an arbitrary condition.

In a typical run (see Figures 10, 11 and 12 above), food accumulates in the environment in the early stages and the A and B populations grow quickly as long as more food appears in each time step than is consumed by them. This population growth comes to an end when the food consumption rate starts to exceed the food production rate. At this point, hungry A's and B's either die or combine to form more advanced species. Those of the new automata that can successfully compete for enough food survive and multiply, whereas the unsuccessful ones repeat the cycle of death or further coalition formations. Thus, a period of great variety in the species populations follows before a steady state is reached in which a relatively small number of successful species survive.

One of the initial unknowns in the development of a model like Eve-1 is how large a universe and how many time steps will be required before non-trivial, consistent results will be obtained. In this case, it was determined empirically that a square universe consisting of 30 x 30 = 900 nodes would yield such results in all cases, and that a steady state could be reached in a few hundred time steps. Information of this sort is of great value, and may in itself constitute an important result of developing and experimenting with Eve-1. It is perhaps only with such items of experience that the intuition required to design more sophisticated stochastic models and explore their potential uses can be developed.

3-3.2. Description of Some Selected Computer Runs

a. Simple Evolutionary Runs

In the very first simulation run with Eve-1, all species were set to have the same metabolic rate and all food particles the same value. In this case, greater capability (i.e., greater range of RS and RM) was not more expensive metabolically, and more advanced species quickly evolved from initial populations of A's and B's until the most advanced species, X, was generated and ultimately dominated the universe.

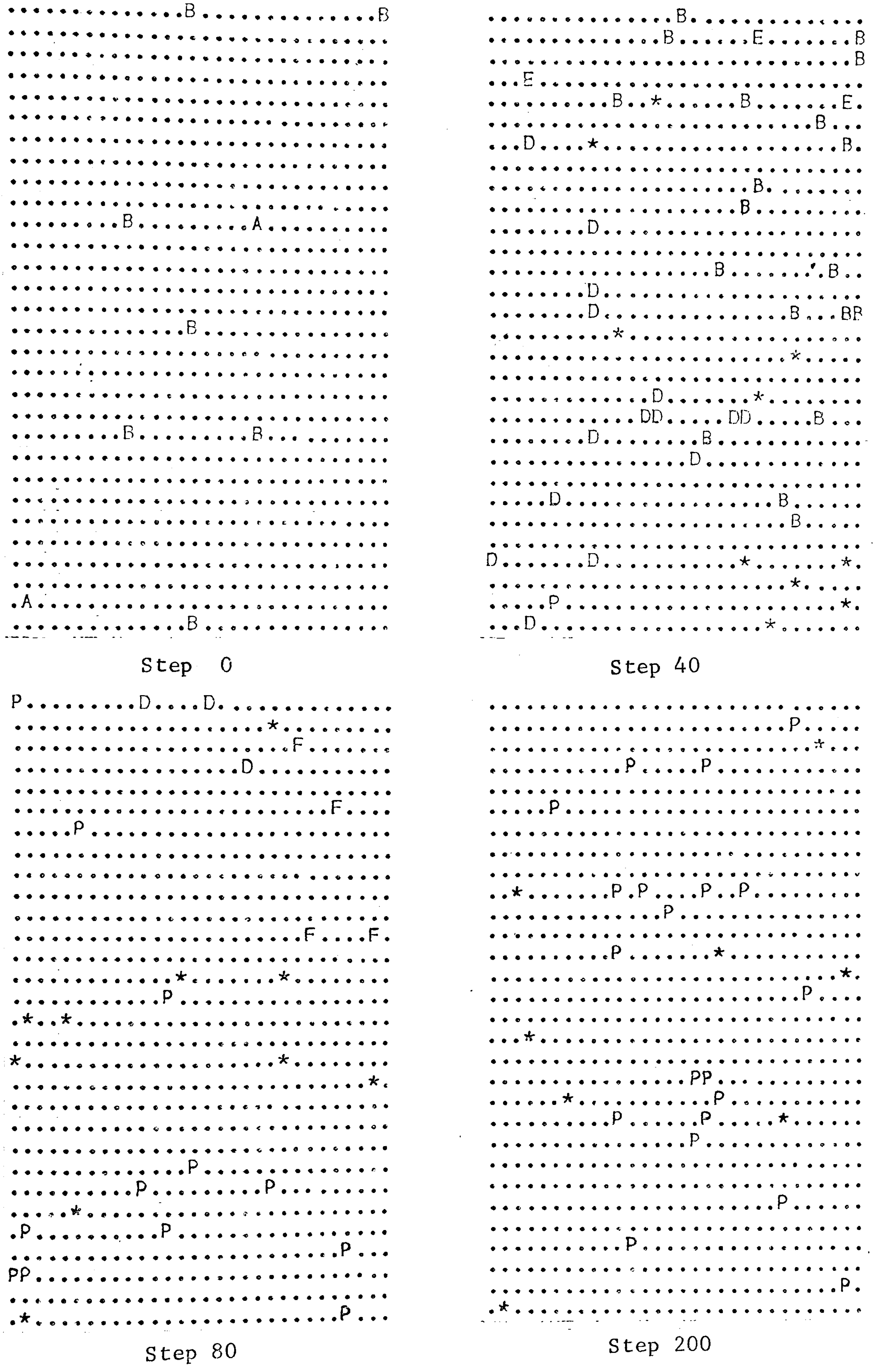
The next simulation attempted was that defined in Figure 9, whose relevant behaviors were shown in Figures 10, 11, and 12 in previous sections. In this simulation, food particles were again of the same value, but the more advanced species were metabolically more expensive. Again, however, X prevailed after a short time, as may be seen in Figures 10, 11, and 12. Clearly for that particular food availability pattern, X would always prevail as long as it remained metabolically viable (i.e., as long as its metabolic rate was kept lower than the value of the food particles). Indeed, when in subsequent runs the metabolic rate of X was raised to a value higher than that of the food particles, species O or species V prevailed (for relative position on species matrix, tabulation of species labels, and other characteristics see Figure 9 on page 110). When species X, O, and V were all made metabolically expensive, species H or species T became dominant. Thus, although some prevalence of vision over movement (species V, T) was seen, species with equal vision and movement capabilities (X, O, H) were also seen to prevail in certain runs. This ambivalence was not fully understood until further insights into the operation of the model were gained with subsequent runs (see below). In any case, the particular runs referred to above clearly emphasized the relative aspect of fitness in that under different environmental conditions entirely different species emerged as dominant.

b. Vision and Movement Capabilities Prevail in Different Environments

In order to study the relative usefulness of vision and movement under different environmental conditions, several runs were made in which all species with advancement levels of 5 and above were defined as metabolically unviable. This restricted the total variety of species to the top left half of the species matrix (see Figure 9), but had the desirable effect of producing a greater variety in most advanced viable species (those with advancement level 4, i.e., species W, L, H, K, P). Being equally advanced, these species had equal metabolic costs but varied dramatically in their vision and movement capabilities. Thus for Q, RS = 1 and RM = 5; for P, RS = 5 and RM = 1; the other three have intermediate values for their seeing and movement radii. The food particles were again kept equal in value.

Using this particular version of the model, several runs were made with different food availability patterns. These runs fell into three categories, and a typical one of each is described below.

In the first category are runs in which food particles appeared in very small numbers (maximum of three per time step), but had a relatively high value (typically 150). Figure 13a shows "snapshots" and Figure 13b vital statistics for the initial state, and for steps 40, 80, and 200 of one of these runs. The results were as might be expected: the scarcity of food particles in the environment made vision more important than movement, and, after the usual period of emergence of a variety of species, evolution proceeded along the top row of the species matrix (see Figure 13b), where species have the minimum movement capability (RM = 1). The most prevalent species, P, has RS = 5, RM = 1, hence it can see five times further than it can move in one step. If it sees a food particle at the perimeter of its range of vision, it will home in on it and capture it in five time steps (unless, of course, another automaton gets to the food particle first). In some such runs species I predominated instead of species P, indicating that under the same food availability



Step 0

Step 40

Step 80

Step 200

Figure 13a: Snapshots of steps 0, 40, 80 and 200 of a simulation showing prevalence of vision over movement. (See also Figure 13b on following page).

```
 STEP   AUTOM    FOODP   CREATED   COMBINED  DIED
  0        9        0        9         0        0   %
-----------------------------------------SPECIES POPULATIONS
       RS=1  RS=2  RS=3  RS=4  RS=5
RM=1     0     2     0     0     0              ?    A    D    I    P
RM=2     7     0     0     0     0              B    C    F    K    R
RM=3     0     0     0     0     0              E    G    H    M    T
RM=4     0     0     0     0     0              J    L    N    O    V
RM=5     0     0     0     0     0              Q    S    U    W    X


 STEP   AUTOM    FOODP   CREATED   COMBINED  DIED
  40      38       11       67         9       29   %
-----------------------------------------SPECIES POPULATIONS
       RS=1  RS=2  RS=3  RS=4  RS=5
RM=1     0     0    15     0     1              ?    A    D    I    P
RM=2    19     0     0     0     0              B    C    F    K    R
RM=3     3     0     0     0     0              E    G    H    M    T
RM=4     0     0     0     0     0              J    L    N    O    V
RM=5     0     0     0     0     0              Q    S    U    W    X


 STEP   AUTOM    FOODP   CREATED   COMBINED  DIED
  80      19       10      113        34       94   %
-----------------------------------------SPECIES POPULATIONS
       RS=1  RS=2  RS=3  RS=4  RS=5
RM=1     0     0     3     0    12              ?    A    D    I    P
RM=2     0     0     4     0     0              B    C    F    K    R
RM=3     0     0     0     0     0              E    G    H    M    T
RM=4     0     0     0     0     0              J    L    N    O    V
RM=5     0     0     0     0     0              Q    S    U    W    X

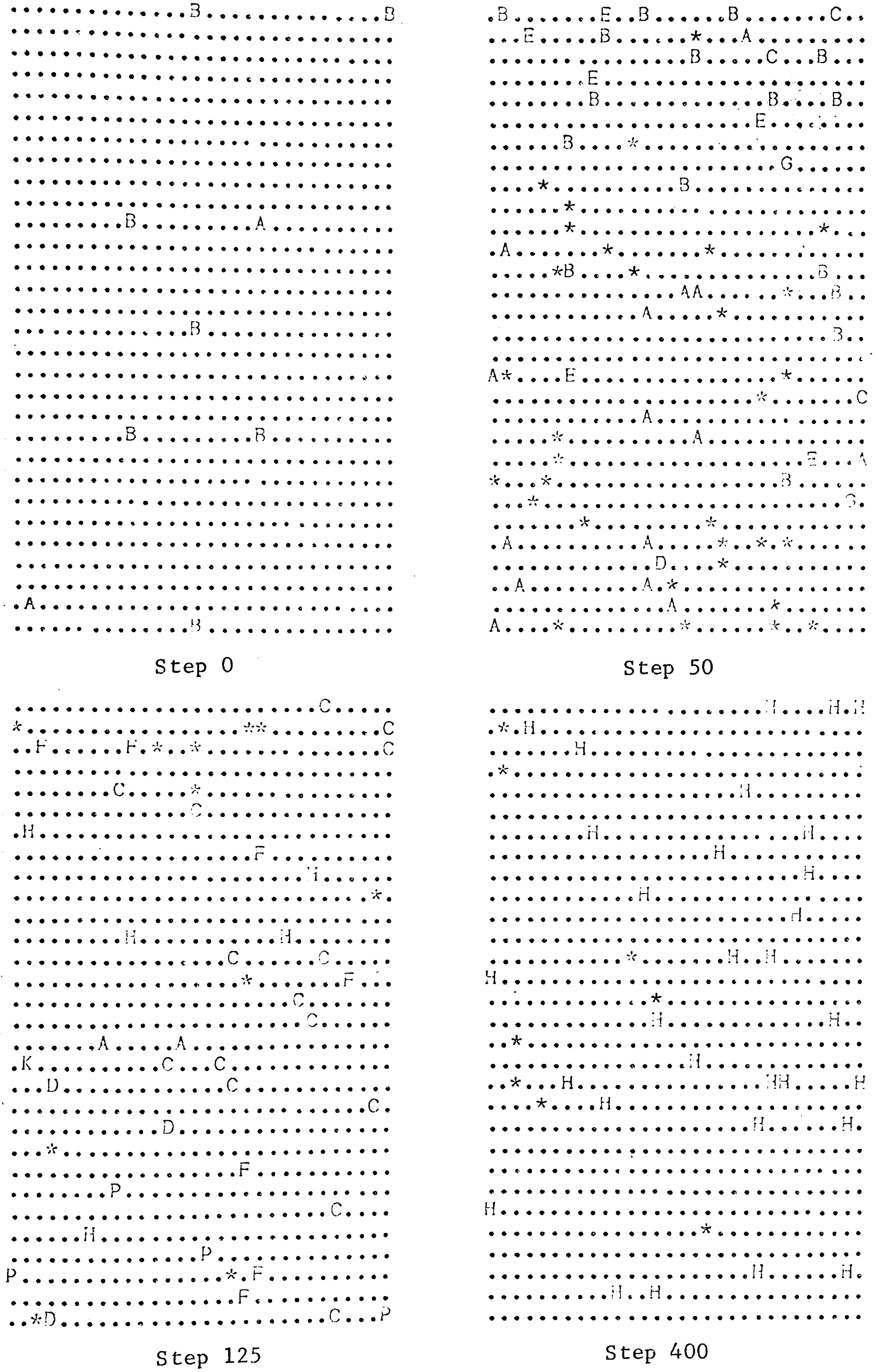

 STEP   AUTOM    FOODP   CREATED   COMBINED  DIED
 200      20        8      217        71      197   %
-----------------------------------------SPECIES POPULATIONS
       RS=1  RS=2  RS=3  RS=4  RS=5
RM=1     0     0     0     0    20              ?    A    D    I    P
RM=2     0     0     0     0     0              B    C    F    K    R
RM=3     0     0     0     0     0              E    G    H    M    T
RM=4     0     0     0     0     0              J    L    N    O    V
RM=5     0     0     0     0     0              Q    S    U    W    X
```

Figure 13b: Vital statistics for steps 0, 40, 80 and 200 of the simulation showing prevalence of vision over movement.

pattern P's longer radius of vision is not enough of an advantage to make up for its greater metabolic cost.

In the second category of this group of simulations, the number of particles entering the environment per time step was increased (to about 10) whereas their food value was reduced to 50. Figures 14a and 14b show a typical run at steps 0, 50, 125, and 400. Here it is clear that movement and vision seem to be equally useful, since evolution proceeds through C to H, in both of which RS = RM. H is the most advanced viable species in this group of runs with equal RS and RM, and it remains dominant.

Finally, Figures 15a and 15b show an example from the third category of runs. Here, a very large number of food particles (NFOOD = 250) is introduced with each time step, and the particle food value has been decreased to 25. Now food particles are almost everywhere, and there is a high probability that one will appear on a node already occupied by an automaton, or immediately next to it. Vision, therefore, is no longer critical (in fact, it's quite useless) and, for that matter, so is great movement capability. The dominant species turns out to be B, one of the two simplest ones, with RS = 1 and RM = 2. Since food is now so plentiful, selection is less severe. Accordingly, a larger number of different species exist at steady state, but as the vital statistics at step 400 (Figure 15b) show, they become less populous the further they are from B on the species matrix. The fact that random movement beyond the radius of vision may be



Step 0

Step 50

Step 125

Step 400

Figure 14a: Snapshots for steps 0, 50, 125 and 400 of a simulation showing equal usefulness of vision and movement. (See also Figure 14b on following page).

```
STEP    AUTOM     FOODP    CREATED    COMBINED    DIED
  0         9        0         9          0          0   %
--------------------------------------------SPECIES POPULATIONS
        RS=1  RS=2  RS=3  RS=4  RS=5
RM=1      0     2     0     0     0              ?     A     D     I     P
RM=2      7     0     0     0     0              B     C     F     K     R
RM=3      0     0     0     0     0              E     G     H     M     T
RM=4      0     0     0     0     0              J     L     N     O     V
RM=5      0     0     0     0     0              Q     S     U     W     X
```

```
STEP    AUTOM     FOODP    CREATED    COMBINED    DIED
 50        43       32        96         25         53   %
--------------------------------------------SPECIES POPULATIONS
        RS=1  RS=2  RS=3  RS=4  RS=5
RM=1      0    15     1     0     0              ?     A     D     I     P
RM=2     16     3     0     0     0              B     C     F     K     R
RM=3      6     2     0     0     0              E     G     H     M     T
RM=4      0     0     0     0     0              J     L     N     O     V
RM=5      0     0     0     0     0              Q     S     U     W     X
```

```
STEP    AUTOM     FOODP    CREATED    COMBINED    DIED
125        37       11       190         74        153   %
--------------------------------------------SPECIES POPULATIONS
        RS=1  RS=2  RS=3  RS=4  RS=5
RM=1      0     2     3     0     4              ?     A     D     I     P
RM=2      0    15     7     1     0              B     C     F     K     R
RM=3      0     0     5     0     0              E     G     H     M     T
RM=4      0     0     0     0     0              J     L     N     O     V
RM=5      0     0     0     0     0              Q     S     U     W     X
```

```
STEP    AUTOM     FOODP    CREATED    COMBINED    DIED
400        30        8       452        178        422   %
--------------------------------------------SPECIES POPULATIONS
        RS=1  RS=2  RS=3  RS=4  RS=5
RM=1      0     0     0     0     0              ?     A     D     I     P
RM=2      0     0     0     0     0              B     C     F     K     R
RM=3      0     0    30     0     0              E     G     H     M     T
RM=4      0     0     0     0     0              J     L     N     O     V
RM=5      0     0     0     0     0              Q     S     U     W     X
```

Figure 14b: Vital statistics for steps 0, 50, 125 and 400 of the simulation showing equal usefulness of vision and movement.

```
B.............B..............B
..............................
..............................
..............................
..............................
A.............................
..............................
..............................
..............................
..............................
A........B.........A..........
..............................
..............................
..............................
..............................
..............B...............
..............................
..............................
..............................
..............................
.........B.........B..........
..............................
..............................
..............................
..............................
..............................
..............................
..............................
.A............................
..............B.........A....B
```

Step 0

```
..*.BB...B***************B...B
.....A.B.B*************B*....B
.AA..A.B.*B.*******..*.*B..*..
.B...ABA**.B.***B***B.**A*AA..
A*AA..*.B*..B**.**.*BBAA**A...
........*..B***.*B*B..*...B....
AA.....AB...*****..B*B*.*.B.AB
**.A*****..*****..*B***...A.*.
.*******AA.***..*****BB***A.A*
*.*.A***.***.A*****..B.**....*
*******.*A*.BA.*BB********.*.A
******.****B...*..B**..B*.***.
****.***.**B.**..B.B....**B**A
**********...*.**.*..B..BB***B
**********...**B..B*B*..B***.*
*********BB.*B*..B..****B**.BB
*********B***..*..BB..*****...
**********.*****B*....*.******
****************.B......****BB
*****************B*BBB..**...A
********************.B.B....B.
*******A************B*.B...B..
******A*************B*.*......
*****.***********.BB.BA.*.BBBB
******AA*******.*..*.B**..A*..
***A*..***A******.B*..*..AA...
**A....A*.********..A.**BA.A.B
**A......*******B*BB..**B.....
A.*.*...*********B*.B.*.B.B..B
*..AA*.***********A.AA****.B.B
```

Step 25

```
....B..A...B.CE.B.BBBBB..B.JBB
D..C...E..BBA...B.....EBQ..B..
A.B......BBBB.BBBB.....A...JA.
A.P.B....J..B*.K...BB..B..AELB
D...FLBB.B.BB...BA...A.B...B..
GAADD..BA...EB...CJ..QB.B.B.BE
A.A.AC.E.A.....*.AB..A.BB....A
BA..B.B..A.U.AB.B.BAB..B..A.B.
..B...AALC.B.BB..*CB..E..BBBBB
AAA.D...AA.BBBCA...B.DBAB.BBA.
.BB..AB.........B.BBA..A.....E
A....C.ABDAA..BB...*BB.A..B..B
A.AAAB.B..*.....B..BB.BE.BBBBA
A..DBD..AD..BBBABE..BCBB.*B..B
AAABB...*..S....B.....A..B..BJ
....BAB...AEAB.BC..B.....B.BBB
...A.A....BB...B.A.B.B.A..BB..
AA..C..........B*...A.BB.BBE...
C.B..A..CB...*..B.C..BBBCBBB..
.A....A..B.C**.B..BBJ..B.....B
DA.ABB..BA.BB..BEB.EB...BBA.B.
.A....A..CCBC.A.C...CA.A.....B
.A...AAABBBB.*A...B..B..AB...B
PEAAA.AAA.E..BA....AA..ABB.BB.
..D.AA....A.C....B.JC.BA..B.B.
AJA.AA.AA.L...AG.B.B..A.E..B..
A..A.A....D.B.....BB..CABB..A.
T.F....A.A.B.B.BABBA.AAA.B...A
AA..AB..AB.EB...A.A..AE.C....A
AA.F.D.A.A..AAA..A.B..AB.E..BJ
```

Step 75

```
....*B..BB...E*.....BB.EBJB..*
C.*....B..B.B.BBBBB...B.BEEB..
.L*C..BCB.E......BE..EB.BEJ..B
*B...BBBAE.E.B..*..B.QB..EB.BB
CCAB....B.BB.EQ..B.....BBJ.BEB
..E..C..B.B.*B....BB..BBB*.BB.
.CC.C......J*J....BBJC.JBBB.B.
.JC.B..........B.B..E.B.B...B.
...DC.B.CBEB...BABB..B..B.....
CBK......B*B.BB..BB..J..*B..B.
FCCC..S..BBB.*.......E.B...BBJ
..A.BC....BB.BB.BB..BB.B..B..J
...AG.S.B..BBBB..B..BCA.A.ABB.
B....C....DB.B.*.*.B..B...E..B
C....B....B....B....A.A.AECBB.
A.A..*AB.*......A..B.B.....BB.
.BF..BA.C...B..E..BB.A.......B
K.A...A..A..W..B.BBB.BEB..EB..
C.DC.FCSA.AABA.B...*B....AB..B
FAAA...C.A..BA.C.AA......*E.*B
.....DCE......AC.B.BB.B.....A.
.AA...DA..B.BA..AH..BB.**.B.*.
AC..A..**.AABAE..EB.BBBABA..B.
A.CBACAB....A..AABBB.AA..E....
...CC.AA.C...BB.D..B....LB.DAA
.DAAA.A...S.F.....AJ.....B..B
.C..A.DC.A.......G..A.A...A...
..AV.FA.C.CACAA..AACBB..AA.B.F
LFA...AA..A.AA...BC...A..BCAB.
...CA.A.F.PA.....AA.......C..B
```

Step 300

Figure 15a: Snapshots of steps 0, 25, 75 and 300 of a simulation showing prevalence of movement over vision (See also Figure 15b on following page).

```
 STEP   AUTOM    FOODP  CREATED  COMBINED  DIED
  0       14       0      14        0        0    %
-------------------------------------------SPECIES POPULATIONS
        RS=1  RS=2  RS=3  RS=4  RS=5
RM=1     0     5     0     0     0          ?    A    D    I    P
RM=2     9     0     0     0     0          B    C    F    K    R
RM=3     0     0     0     0     0          E    G    H    M    T
RM=4     0     0     0     0     0          J    L    N    O    V
RM=5     0     0     0     0     0          Q    S    U    W    X
```

```
 STEP   AUTOM    FOODP  CREATED  COMBINED  DIED
  25     153      491     153       0        0    %
-------------------------------------------SPECIES POPULATIONS
        RS=1  RS=2  RS=3  RS=4  RS=5
RM=1     0    54     0     0     0          ?    A    D    I    P
RM=2    99     0     0     0     0          B    C    F    K    R
RM=3     0     0     0     0     0          E    G    H    M    T
RM=4     0     0     0     0     0          J    L    N    O    V
RM=5     0     0     0     0     0          Q    S    U    W    X
```

```
 STEP   AUTOM    FOODP  CREATED  COMBINED  DIED
  75     419      35      607      171      188   %
-------------------------------------------SPECIES POPULATIONS
        RS=1  RS=2  RS=3  RS=4  RS=5
RM=1     0   134    14     0     2          ?    A    D    I    P
RM=2   199    25     3     1     0          B    C    F    K    R
RM=3    21     2     0     0     1          E    G    H    M    T
RM=4     9     4     0     0     0          J    L    N    O    V
RM=5     2     1     1     0     0          Q    S    U    W    X
```

```
 STEP   AUTOM    FOODP  CREATED  COMBINED  DIED
 300     388      45     1938     1261     1550   %
-------------------------------------------SPECIES POPULATIONS
        RS=1  RS=2  RS=3  RS=4  RS=5
RM=1     0    90     9     0     1          ?    A    D    I    P
RM=2   178    46     9     2     0          B    C    F    K    R
RM=3    27     2     1     0     0          E    G    H    M    T
RM=4    12     3     0     0     1          J    L    N    O    V
RM=5     2     4     0     1     0          Q    S    U    W    X
```

Figure 15b: Vital statistics for steps 0, 25, 75 and 300 of the simulation showing prevalence of movement over vision.

advantageous (as it is in this case) may seem paradoxical. It becomes plausible, however, when we consider the very high concentration of food particles; if there is no food particle within an automaton's range of vision, there is a high probability that a move away from the food-depleted location will bring a food particle into view even if the move is random. Some further remarks pertinent to this particular result are included in section 3-4.2 below.

c. Variety in the Environment Creates Ecological Niches and Induces Symbiosis of Species

In another group of simulations, food particles of different sizes were introduced. As previously explained, this is done by assigning each new food particle a random value lying in a prespecified range. This feature becomes meaningful if the range of food values overlaps with the range of metabolic rates of the species, since an automaton cannot eat (or even see) particles the values of which are lower than its metabolic rate. Now the smaller food particles may be eaten only by "small" automata, and if they remain uneaten they continue to occupy positions in which other food particles cannot appear. All automata still compete, however, for the larger food particles, so although niches exist for the less advanced species, competition is still present. This kind of model can yield two kinds of results, both of which were actually observed.

In the first case, exemplified by the runs shown in Figure 16a and 16b, the food availability partern induces the

Step 0

Step 80

Step 300

Step 600

Figure 16a: Snapshots of steps 0, 80 300 and 600 of a simulation showing symbiosis of species C, H, O, X. (See also Figure 16b on following page).

```
 STEP  AUTOM    FOODP  CREATED  COMBINED  DIED
  0        4      0        4        0        0   %
---------------------------------------SPECIES POPULATIONS
       RS=1 RS=2 RS=3 RS=4 RS=5
RM=1    0    2    0    0    0              ?    A    D    I    P
RM=2    2    0    0    0    0              B    C    F    K    R
RM=3    0    0    0    0    0              E    G    H    M    T
RM=4    0    0    0    0    0              J    L    N    O    V
RM=5    0    0    0    0    0              Q    S    U    W    X
```

```
 STEP  AUTOM    FOODP  CREATED  COMBINED  DIED
  80      51     59      119       35       68   %
---------------------------------------SPECIES POPULATIONS
       RS=1 RS=2 RS=3 RS=4 RS=5
RM=1    0   16    2    0    0              ?    A    D    I    P
RM=2   16    9    3    1    0              B    C    F    K    R
RM=3    2    1    0    0    0              E    G    H    M    T
RM=4    1    0    0    0    0              J    L    N    O    V
RM=5    0    0    0    0    0              Q    S    U    W    X
```

```
 STEP  AUTOM    FOODP  CREATED  COMBINED  DIED
 300      39     49      246      106      207   %
---------------------------------------SPECIES POPULATIONS
       RS=1 RS=2 RS=3 RS=4 RS=5
RM=1    0    0    0    0    0              ?    A    D    I    P
RM=2    0   14    1    0    0              B    C    F    K    R
RM=3    0    0   17    0    1              E    G    H    M    T
RM=4    0    0    1    2    2              J    L    N    O    V
RM=5    0    0    0    0    1              Q    S    U    W    X
```

```
 STEP  AUTOM    FOODP  CREATED  COMBINED  DIED
 600      36     68      374      178      338   %
---------------------------------------SPECIES POPULATIONS
       RS=1 RS=2 RS=3 RS=4 RS=5
RM=1    0    0    0    0    0              ?    A    D    I    P
RM=2    0   11    0    0    0              B    C    F    K    R
RM=3    0    0   16    0    0              E    G    H    M    T
RM=4    0    0    0    6    0              J    L    N    O    V
RM=5    0    0    0    0    3              Q    S    U    W    X
```

Figure 16b: Vital statistics for steps 0, 80, 300 and 600 of the simulation showing symbiosis of species C, H, O, X.

Figure 17: Time plots showing species populations in the simulation shown in Figures 16a and 16b.

symbiosis of species C, H, O, and X, all of which have each equal movement and vision capabilities. Figure 17 shows a plot of the species populations vs. time for the same run. All of the species populations are evenly dispersed in the environment during symbiosis.

In the second case, shown in Figures 18a and 18b, the food particle value range was shifted down so that the smallest value was equal to the metabolic rate of species A and B. This meant that A and/or B had to survive in the steady state if the whole ecosystem were to be viable in the long run. As is evident from Figure 18b, however, both A and B have disappeared by step 300. This is because A and B have to compete with each other for the few food particles that are edible only by them, and with the more advanced species, for the larger particles. They are unable to do so successfully, however, and eventually their populations perish. Now there are no automata to eat the small food particles, which consequently accumulate continuously, making less and less space available for the larger particles feeding the more advanced automata (H, O, X). At this point the fate of the system depends somewhat on chance. If a new small automaton is generated through a coalition formation between more advanced automata (e.g., $H + M \rightarrow X + A$), then it will quickly multiply and "clean up" the environment of all small particles. Otherwise the trend of clogging up the environment with small food particles will continue. Note that, at step 300, the species H and M are present, so the possibility of

```
..............................
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..............................
..............................
..............................
.........B.........A..........
..............................
..............................
..............................
..............................
..............................
..............................
..............................
..............................
..............................
.........B.........A..........
..............................
..............................
..............................
..............................
..............................
..............................
..............................
..............................
..............................
```

Step 0

```
...*V**.**.**HX**.........*C..
.....**.*..**..*..*...........
.*............*...............
*.**...*..*....H....*.........
C..*..**.....*.............*..
............**.....*..C...*...
V*.........C**.*...*.C*...*.*.
.*...............C............
**..*.....*......*...*........
...**.**.....*......*.........
...*.*..........*..H..*...*...
..*.M....*........*.X.*.......
....**..*.C...*......*..*..C..
...**..V**...*..*..*..*.....*.
...*.H*....*.*....C.*.*...*..*
...*..*.**.*H..*.O.*..*...*...
.....*..**.*...*......**.*....
.F..**.....*...*.............*
**........*...*........*.C.*..
...*..*..**......C..*.**......
..*......*......*O.*......*..*
.**.........*..*..**.**......*
.*......*..*..C...*..*..**....
*..*...*......*.....**..*..*.*
*..*..C......*.....*.........*
..*....X..H.**...X.*.....**.**
.............*...........*..*.
...C..............*..*..X*..*.
.*..*...............*...*.F*.*
*.........*C........*..*...*.*
```

Step 300

```
**********..**.**..**.**.**.**
*********..**.**..**.**.**..**
***.*****..*..**.**.**..**.**.
**.*****H.**.**.**..**H**.**..
*..**.**.**.**.***.**.**.H**.*
*.**.**..*..**.**..*..**.**.**
.**.**..*...**.*..**..*.**..**
**.***.**..*..**.....*..*X.**.
**.***.HH.**.**.**..**.**.**..
****..**..*..*..**.**.**..**.*
*.**.**..*..**.**..*..H..**.**
.*****..**.***.*..*...*..*..**
**.******.**..*..**.**..**.**.
*****.**.***.**..*..**.**.**..
****..**.**.**..*..**.**..*X.*
*.**.**.**..**.**..*..**.**.**
.**.**H.**.**..*..**.**.*H..**
**..**H**.**..**.**.**..**.**.
**.**..*..**.**..*..*..**.**..
*.**..**.**.**..H*.**.**..**.*
..**.**..*..**.**H**..**.**..*
.**.**..**.**..*..*****.**..**
**..**.**.**..**.**H**..**.**.
**.*H.**..H*.**.**..**.**.**..
*.**..**.**.**..**.**.**.***.*
..**.**..*..**.**.***.**.**..*
.**..*..**X**.**..**.**.**..**
**..**.**..*..*..**..*X.**.**.
**.*****..**.**.**..*****.**.*
**.*..**.**.**..**.**.**..****
```

Step 1200

Figure 18a: Snapshots for steps 0, 300, and 1200 of a simulation showing failure of symbiosis and clogging up of the environment with uneaten food particles. (See also Figure 18b on following page).

```
 STEP   AUTOM     FOODP   CREATED   COMBINED   DIED
  0         4       0        4         0          0    %
-----------------------------------SPECIES POPULATIONS
      RS=1  RS=2  RS=3  RS=4  RS=5
RM=1    0     2     0     0     0             ?     A     D     I     P
RM=2    2     0     0     0     0             B     C     F     K     R
RM=3    0     0     0     0     0             E     G     H     M     T
RM=4    0     0     0     0     0             J     L     N     O     V
RM=5    0     0     0     0     0             Q     S     U     W     X


 STEP   AUTOM     FOODP   CREATED   COMBINED   DIED
 300       34      188      224       101       190    %
-----------------------------------SPECIES POPULATIONS
      RS=1  RS=2  RS=3  RS=4  RS=5
RM=1    0     0     0     0     0             ?     A     D     I     P
RM=2    0    15     2     0     0             B     C     F     K     R
RM=3    0     0     6     1     0             E     G     H     M     T
RM=4    0     0     0     2     3             J     L     N     O     V
RM=5    0     0     0     0     5             Q     S     U     W     X


 STEP   AUTOM     FOODP   CREATED   COMBINED   DIED
1200       18      534      473       235       455    %
-----------------------------------SPECIES POPULATIONS
      RS=1  RS=2  RS=3  RS=4  RS=5
RM=1    0     0     0     0     0             ?     A     D     I     P
RM=2    0     0     0     0     0             B     C     F     K     R
RM=3    0     0    14     0     0             E     G     H     M     T
RM=4    0     0     0     0     0             J     L     N     O     V
RM=5    0     0     0     0     4             Q     S     U     W     X
```

Figure 18b: Vital statistics for steps 0, 300 and 1200 of the simulation showing failure of symbiosis and clogging up of the environment with uneaten food particles.

regeneration of A is still there. Such generation does not happen, however, and by step 1200, A and B can no longer be generated. So the small food particles keep accumulating, and, after enough time steps, all nodes in the universe will be found to contain only small food particles. By that time the advanced automata will have also starved to death, victims, in a sense, of their own early high fitness which eliminated the smaller "house cleaning" automata. The population plot for this run is shown in Figure 19, and a clear conclusion is that there is a definite advantage of maintaining a sufficient variety in the ecology for its overall and long range stability. (Some additional remarks about the possible outcomes of this model may be found in section 3-4.1 below.)

It should be emphasized at this point that "collaborative" behavior among automata (that is manifest for example in a symbiotic steady state), is not in any way "explicitly programmed in" in Eve-1, nor are the rules of the model ever changed to reward collaboration explicitly. Symbiosis, when it is observed, is strictly a result of the stochastic operation of the model as defined in earlier sections, and it is for this reason that under certain conditions it fails to materialize even though it would have been the only way for automata to survive in the long run.

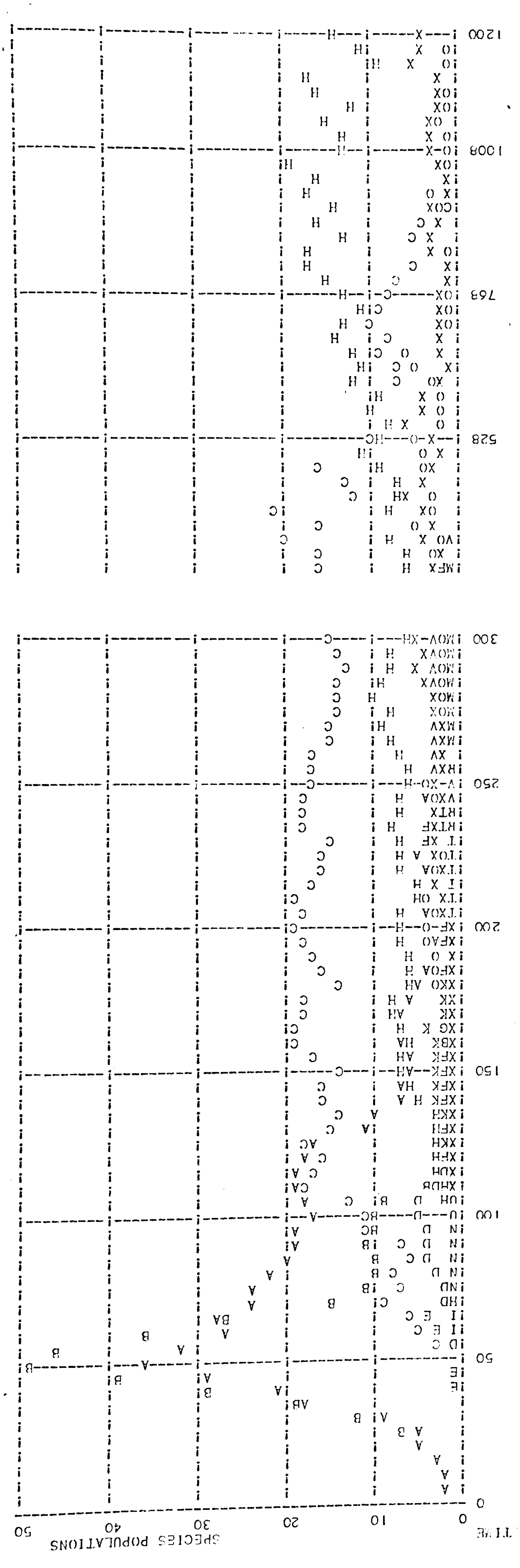


Figure 19: Time plot showing species populations for the simulation shown in Figures 18a and 18b.

d. The Introduction of Barren Territory Accelerates Evolution and/or Favors Vision

In some simulations a temporary modification was introduced to the program preventing food particles from appearing in one-third of the nodes which constitute the universe. Figure 20 shows the vital statistics for a run without this modification, and Figure 21 shows a run where all parameters are the same except that the "barren" territory was introduced. As these Figures show, the introduction of barren territory has introduced prevalence of vision (see, for example, step 500 in both Figures). This is easily understood, since longer vision makes it less likely that an automaton will enter the barren territory, and, in the case that it does enter such a barren territory, a longer vision range would make it easier for the automaton to move back to a territory where food is available, before it starves to death.

In a different set of runs of a similar sort, with different food availability pattern, X predominated both in the presence and in the absence of barren territory--but the evolution from A and B to X took less time in the case when the barren territory was present. This acceleration of the evolutionary process was, of course, due to the fact that more automata found themselves in difficulty (and therefore formed coalitions) from the very beginning of the simulation when much of the territory had no food.

	RS=1	RS=2	RS=3	RS=4	RS=5
RM=1	0	2	0	0	0
RM=2	2	0	0	0	0
RM=3	0	0	0	0	0
RM=4	0	0	0	0	0
RM=5	0	0	0	0	0

Step 100

	RS=1	RS=2	RS=3	RS=4	RS=5
RM=1	0	6	6	3	1
RM=2	6	5	1	0	0
RM=3	3	0	1	1	0
RM=4	0	0	0	0	0
RM=5	0	0	0	0	0

Step 150

	RS=1	RS=2	RS=3	RS=4	RS=5
RM=1	0	0	0	0	0
RM=2	0	13	0	0	0
RM=3	0	0	1	4	0
RM=4	0	0	0	0	1
RM=5	0	0	0	0	0

Step 250

	RS=1	RS=2	RS=3	RS=4	RS=5
RM=1	0	0	0	0	0
RM=2	0	0	0	0	0
RM=3	0	0	5	3	0
RM=4	0	0	0	0	0
RM=5	0	0	0	0	6

Step 500

Figure 20: Species population at steps 100, 150, 250 and 500 for a simulation without barren territory.

	RS=1	RS=2	RS=3	RS=4	RS=5
RM=1	0	2	0	0	0
RM=2	2	0	0	0	0
RM=3	0	0	0	0	0
RM=4	0	0	0	0	0
RM=5	0	0	0	0	0

Step 100

	RS=1	RS=2	RS=3	RS=4	RS=5
RM=1	0	10	5	1	1
RM=2	6	1	1	0	0
RM=3	2	0	0	0	0
RM=4	0	0	0	0	0
RM=5	1	0	0	0	0

Step 150

	RS=1	RS=2	RS=3	RS=4	RS=5
RM=1	0	3	2	0	0
RM=2	0	0	13	1	2
RM=3	0	0	0	0	0
RM=4	0	0	0	0	0
RM=5	0	0	0	0	0

Step 250

	RS=1	RS=2	RS=3	RS=4	RS=5
RM=1	0	0	0	0	0
RM=2	0	0	8	0	0
RM=3	0	0	0	0	5
RM=4	0	0	0	0	3
RM=5	0	0	0	0	1

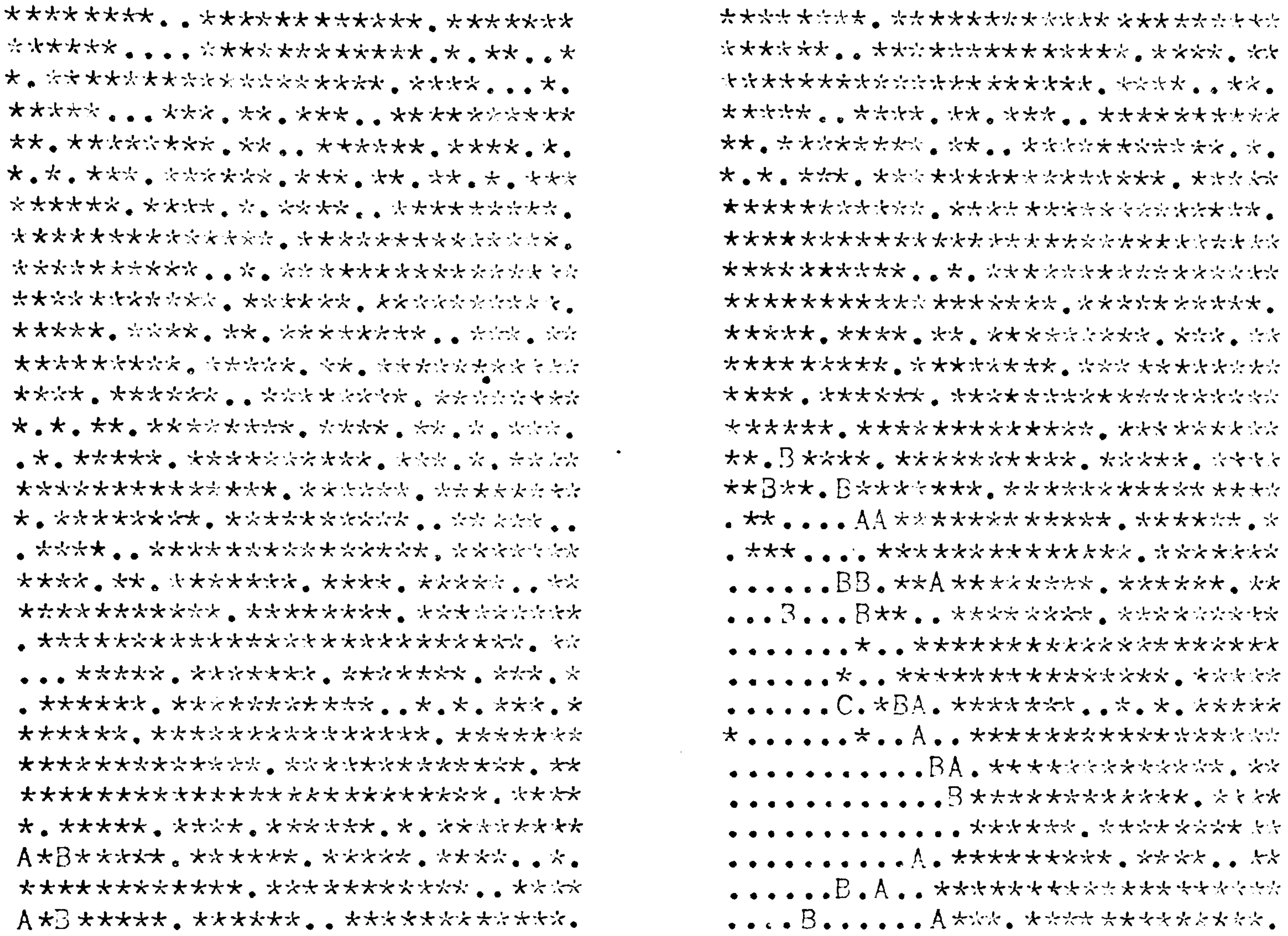
Step 500

Figure 21: Species population in the same steps (0, 150, 250 and 500) when barren territory was introduced.

e. Spatial Uniformity of Population Distribution--And Some Exceptions

Since both the location and the sizes of food particles are selected randomly by the program, one would expect the population of each species to diffuse randomly throughout the environment. This indeed is the case most of the time when steady state is reached in typical runs.

Before steady state, however, and occasionally for brief periods after it is reached, some definite spatially non-uniform patterns may be observed. Figure 22 shows snapshots from one run showing interesting spatial variations. Early in the run, the few automata in existence live and multiply in one portion of the universe, while food accumulates unconsumed in other regions. In time, the automata deplete the food in the region they occupy and begin dying or forming coalitions. At the same time, those automata which are near the "frontier" of the inhabited region discover the food-rich region, and move into it, multiplying at a high rate. The snapshots in Figure 22 show a whole front of such automata actually sweeping this region clean and proceeding almost in formation until they reach the opposite boundary of the universe. Figure 22 also shows that more advanced automata start to evolve in the depleted territory, while most of the "new conquest" is still made by the simpler ones. When the entire field has been cleared of the initial high food concentration, certain regions which have been empty of automata for long enough sometimes become rich in



Step 100

Step 120

Step 140

Step 160

Figure 22: Snapshots of steps 100, 120, 140 and 160 of a simulation showing spacially non-uniform patterns.

food again, and so there starts a similar advance back to these original regions. A definite spatial oscillation is, then, observed, but it dies out, given enough time, when the steady state is reached. (Nevertheless, phenomena of this sort were occasionally seen even after steady state was reached; a temporary disturbance may induce such oscillations, but the same steady state is eventually recovered.)

In one particular case, the observation of a markedly non-uniform pattern was traced to a programming detail that could create anisotropic results in certain situations. Figure 23, for example, shows the early stages of a simulation with a very high food particle production rate. Although the initial state contained a few automata evenly distributed, all populations moved rapidly to one end of the universe while the rest of it became completely filled with food particles. Eventually the automata swept across the entire environment in one almost solid front, but the initial move to one direction, given a uniform initial distribution, was hard to explain.

The problem was finally traced to the program subroutine which searches the region visible by an automaton for the closest food particle. Unlike other similar subroutines, this particular one did not have a randomized search, but scanned the visible region always in the same orderly pattern, always selecting the first of all equidistant closest particles. This type of search would not produce problems in most cases, since it is generally rare that two or more food

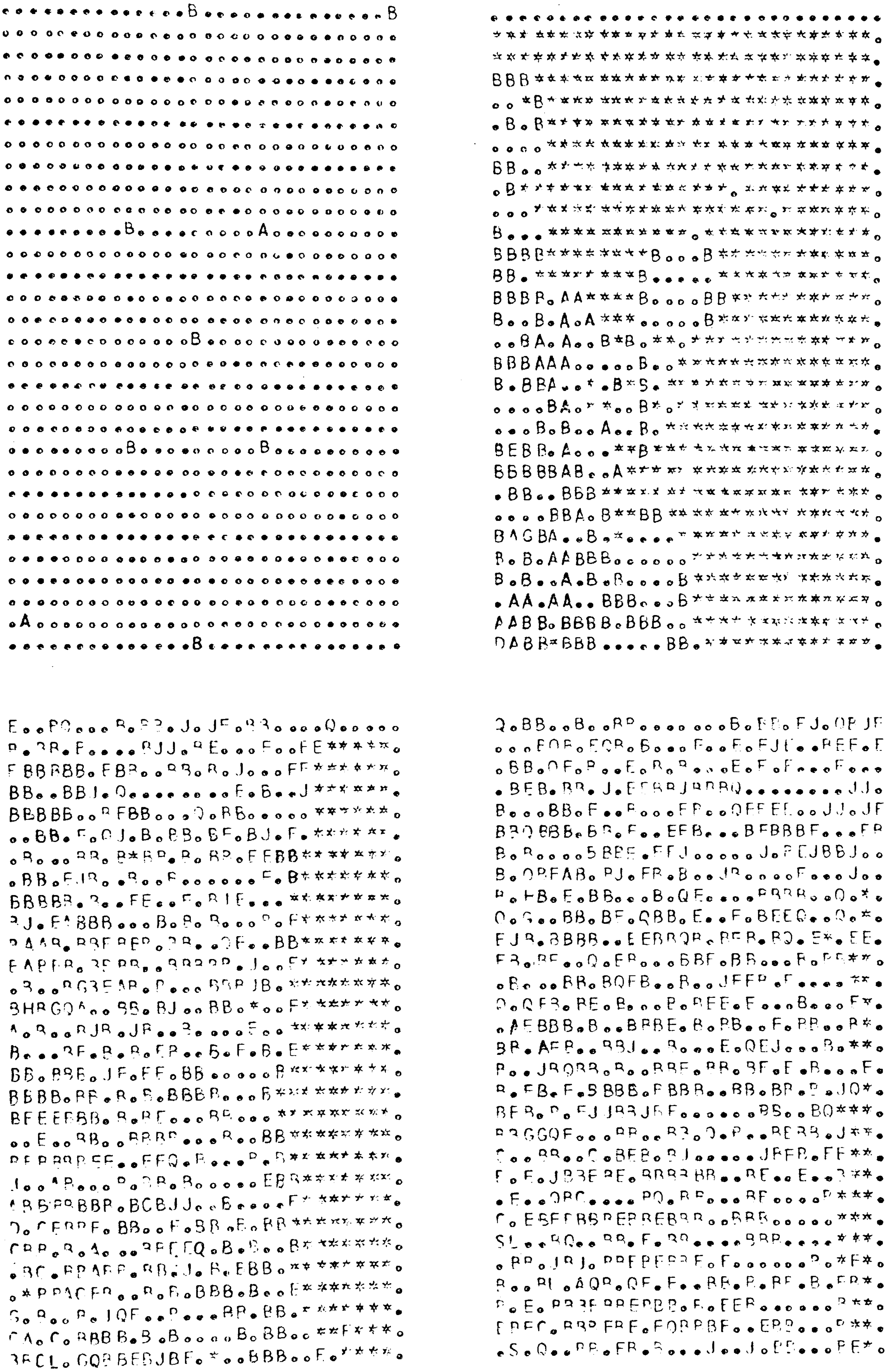


Figure 23: Snapshots for steps 0, 25, 75 and 100 of a simulation showing spurious non-uniform patterns traced to non-randomized rule in an early version of the program.

particles are equidistant from an automaton (and are the closest ones to it at the same time), thus requiring that a choice be made. When, however, there is a very high food concentration and a small number of automata, this particular condition arises often enough to influence the direction of movement of the automata. The problem was removed by introducing a random variable in the choice among equidistant food particles. But this experience exemplifies the care that must be taken in implementing a truly random stochastic model if errors of omission and oversight in the implementation are to be kept from interfering with interpretation of the results.

3-4. General Observations on the Behavior of the Model

A number of general statements may be made in conclusion on the basis of the experience which was gained with Eve-1 to date. These include the following:

3-4.1. Characteristics of the Steady State

Many of the processes occurring in Eve-1 are random: food particles appear at random locations and, in some of the simulations, have random values; automata move randomly whenever they see no food or neighbors, and they search their visible regions in a random order when selecting nearest targets, choosing a neighbor to form a coalition, or looking for a free adjacent node where they reproduce. Nevertheless, a steady state is always reached after a few hundred time steps in which all the viable species populations are evenly dispersed in the environment retaining their magnitudes with remarkable consistency. In practically all cases, only one or very few species are present in significant populations in the steady state--a significant fact, since automata of new species are normally being continuously generated through coalition formation, and furthermore since there is no collaboration among automata of the same species.

The steady state is also characterized by a relatively constant amount of free food in the environment and a stable total population of all species. There are, of course, oscillations about the mean values of these quantities, but these tend to be regular and never large enough to upset the overall system balance. The total system seems to operate as a very efficient control mechanism which quickly attenuates and reverses all local disturbances.

The adaptability and great stability of the statistical steady state of this stochastic system becomes more remarkable when one reflects its relatively low complexity (as compared to any real-world ecological or biological system, for example). Furthermore, it is interesting that this stable steady state is extremely dynamic, as it is characterized by consistently high birth and death rates of automata. (It should be remembered, in this respect, that automata die only of hunger and never by decay due to aging.) All species populations are constantly renewing themselves, and there is a large number of "hunger deaths" even in successful species--all this while the individual species populations remain remarkably constant. In addition, there is always a non-zero rate of coalition formations in the steady state which (except in degenerate cases discussed further in section 3-4.2 below) constantly introduces automata of new species into the system.

One possible exception to the above remarks concerning the steady state could be certain types of systems in which the long term survival of the population of automata depends on the symbiosis of two or more species. As previously mentioned (section 3-3.2.c), in certain cases this symbiosis is stable, and a steady state will be reached; in other cases, however, the symbiosis fails to continue beyond a certain point and eventually all species become extinct; finally, it would be possible for the symbiosis to assume a cyclical pattern in which one or more species may become periodically extinct and be regenerated when their corresponding niches have grown sufficiently. The latter phenomenon has not actually been observed during experiments with Eve-1, although it seems perfectly possible. It seems that by using a larger universe, for example (which would have increased the probability of occurrence of rare events such as the regeneration of a particular species at a particular time), it should be possible to induce such a cyclical steady state.

3-4.2. Evolutionary Pathways and Barriers

In Eve-1, coalition formations are responsible for the generation of new species of automata (as well as, in some cases, of already existing ones). A specific coalition formation event has a random component (the adjacency of two "hungry" automata in a certain time step) as well as a deterministic one. (Its results are uniquely determined by the genotypes of the two automata that form it.)

The deterministic aspect of the coalition formation rules allows for the occurrences of irreversible transitions in the composition of the automata populations. In other words, although every species may be generated as a result of some coalition formation, it is possible that the total system may enter a state after which a particular coalition formation can never occur. This, of course, happens if the types of automata required to bring about such a specific coalition do not exist and cannot themselves be generated for the same reason. Once a system has entered such a state, then the production of certain types of species is not possible any more, and evolution may only proceed along certain restricted "pathways." An evolutionary "barrier" now exists that precludes the generation of certain species, and the species that prevail in the steady state may not be the best equipped to compete for food.

In practice, when the initial state contains species A and B, such barriers are generated only after the model has operated for a considerable number of time steps and is ready to reach its steady state, in which case the number of surviving species would normally be relatively small. Recall that in the early part of each simulation, a relatively large number of species is usually generated, which means that the generation of all species remains possible (and often happens) for a significant number of time steps. Nevertheless, the fact that normally the model will eventually follow restricted pathways is important and it warrants the extension of the concept of fitness in Eve-1. Thus, although the fitness of an individual automaton depends only on its success in competition for food, the fitness of a species population, as a whole, depends also on the stability of the genetically determined evolutionary pathway(s) to which it belongs.

Examples of absence or presence of such pathways may best be discussed with reference to the species matrix (reproduced here for convenience as Figure 24), and of the rules for coalition formation (section 3-2.4.c and Appendix A). It may easily be seen that when species A and B exist (in any numbers) then all other species may be generated. This is true since any species combining with A will increase its sensing gene value by 1 and any species combining with B will similarly affect the value of its movement gene; all species may therefore be generated whenever A's and B's are

G_s value →

G_m value ↓	0	1	2	3	4
0		A	D	I	P
1	B	C	F	K	R
2	E	G	H	M	T
3	J	L	N	O	V
4	Q	S	U	W	X

Figure 24: Species Label Matrix

present, and no restricted pathways are then in effect. There are many other simple cases in which a small number of species can, with successive coalitions, generate all others. For example, species K can generate A as follows:

SYMBOLIC NOTATION	GENOTYPE NOTATION
K + K → T + D	(3,1)+(3,1) → (4,2)+(2,0)
K + D → E + A	(3,1)+(2,0) → (4,1)+(1,0)

Similarly, species L can generate B, so in effect K and L together are also capable of generating all other species.

On the other hand, species C and H can only generate the set{C, H, O, X}, therefore a restricted pathway will be entered when only C's and H's survive in an environment. Other sets of species defining restricted pathways include {A, D, I, P}, {B, E, J, Q} and {A, D, I, P, K, R, T, V, X}. The first of these is a subset of the third one, indicating that a restricted pathway may further restrict itself if certain of the species that define it (in this case K, R, T, V, X) become extinct.

The existence of restricted evolutionary pathways in Eve-1 illustrates the possibility that an evolving system may "trap" itself and lose its adaptability if it allows itself to lose redundancy in an effort to optimize its performance in response to a specific set of conditions. If the food availability pattern is drastically changed when a simulation has entered its steady state, the system may not be able to generate the species (variety) that could "handle" the new conditions in an optimal way. This kind of limitation could be removed, or made less severe, by introducing into the model the concept of random mutations or by changing the coalition formation rules. This was not done, however, since the existence of the evolutionary pathways was felt to make the model more useful, corresponding as it does to various biological and certainly social pathologies. It should also be noted that, if niches for species A and B are defined (as described earlier), then A and B will never disappear entirely and the flexibility of the whole system will not be lost.

3-4.3. Efficiency of the Total Population of Automata

As previously mentioned, the fact that food appears exogenously in Eve-1 makes it possible to define a measure of efficiency of the total population in maintaining as little unconsumed food in the environment as possible. As long as the food availability pattern does not change, evolution in the model seems always to follow a path that decreases this amount of free food. (Initially, of course, there is a period during which free food accumulates; this is because the system takes a while to correct the inefficiencies usually contained in the externally defined initial state.) With the minor modifications mentioned at the end of the previous section, it would be possible to make Eve-1 maximize efficiency even when the food availability pattern changes drastically.

This increasing efficiency may be interpreted as a goal of the total system; however, it is important to emphasize that this goal has not been explicitly programmed into the model, neither at the macroscopic nor at the microscopic level. Furthermore this phenomenon suggests at least the possibility that stochastic systems of this type could be developed as control systems for real-world applications, specifically in cases where the environment is characterized by randomness and great variety. In a similar vein, such models could also be used as tools for the solution of complex design problems (in structural design, for example) where direct analytical or numerical methods cannot be applied.

3-4.4. Evolutionary Events in Eve-1: An Interpretation

Evolutionary events in Eve-1 occur through the formation of coalitions which is brought about by simple automata combining to form more complex ones. The degree of complexity is arbitrarily defined with respect to the primary properties of such automata, namely vision and movement, and while these have a specific meaning for survival efficiency relative to the particular environment defined in the model, they are intended to stand as general tokens for any property which may increase survival advantage. For example, these properties may be regarded as different states that a system can assume as it meets environmental challenges and they may thus be taken to represent a system's behavioral repertoire, or, in other words, its total effective variety. Variety in this context is meant in the sense of a measure of the actual number of different "moves" a system can make in its "struggle" for survival, where a "move" may stand for a behavioral strategy, an actual action, and so forth.

The formation of a coalition, therefore, always involves an increase in such variety interpretable as an increase in available behavioral possibilities, which increase results in a higher survival advantage. In the model this is manifest in the condition whereby initial simple elements, once they are generated in the universe, tend to form more complex aggregates. Like their subcomponents, these can reproduce and they become subject to further selection in themselves.

The evolutionary event of forming a coalition can be interpreted with respect to the general problem of resolving undecidable situations. A system A_1 may encounter a situation in which the object language L_{a1} of its interaction with an environment is proven insufficient for handling a novel circumstance which may threaten its survival. The repertoire available to A_1 in L_{a1} may be such that it simply does not contain the vocabulary essential for maximizing survival pay-offs under the new conditions. In such an event, and particularly if the problem persists because of scarce resources, for example, the system may either stagnate and eventually perish, or it may evolve into a more complex system A_2 with a more comprehensive object language L_{a2}. Relative to the previous system, the new L_{a2} may be regarded as a metalanguage within the scope of which the situation can now be resolved. Such an effective resolution is in itself a source of a selective reward which encourages the evolutionary trend from A_1 to A_2.(46)

In the model, an undecidable situation is encountered when an automaton finds itself in a condition in which its available behavioral repertoire (the specific capabilities of vision and movement) is insufficient to secure an adequate food supply. In such a case it can survive only if it will form a coalition, the new combined properties of which (again with specific respect to vision and movement) may now make possible the capture of food particles within the allotted critical time limits. From the viewpoint of the "organizational model" (see Appendix D), the general implications of such an event are clear. If a system's interaction with its environment is stable (homeostatic) and if there are sudden changes in environmental circumstances, a radically different type of organization may be required if survival is to be ensured. In such an event, a change in organizational structure will also entail a change in the procedures (programs) regulating the system's behavior. In other words, the appropriate 'language' must evolve synchronously with the prosessor. (A change in structure, or form, for example, but not in content, is a common institutional pathology.)

This remark is applicable to viable systems in general and while it may clearly relate to biological evolution, it is particularly relevant to the domain of human social systems. In this level, coalition formation, interpreted in its broadest sense, plays a major evolutionary role. Indeed the great evolutionary advangage of man lies precisely in a comprehensive strategy which allows him to selectively form and reform coalitions with other men and with other animate or inanimate parts of his environment.

4. SOCIETY AS A BRAIN

4-1. Society as a Product of Evolution

Contemporary concepts of evolution hold that in order to explain the build-up of stable organizations and the general tendency of evolution to proceed in the direction of forming structures of increasing complexity, a principle of "stratified stability" must be assumed. Bronowski, who coined the term (1) argued that the stable organizations which have emerged during the course of evolution must each be regarded as a specific realization of a potential strata of stability, inherent to the variety of possible energy configurations.

The concept is applicable to the sequential build-up of the chemical elements as it is to the emergence and subsequent evolution of increasingly more complex forms of life. It accounts for the general process by which, step by step, simple units interact to form more complex entities and these, in turn, serve as basic components in forming still more complex ones. Each new level of complexity is built on the next lower level which is stable in itself.(2) Each level actualizes a potentially stable configuration and it involves the emergence of novel properties. The process as a whole is conditioned upon a continuous input of energy into the evolving region, and the operation of a process of selection which, especially among life forms, speeds up the realization of intrinsically stable configurations.

Thus, as Bronowski points out, the build-up of the chemical elements proceeds step by step from the formation of hydrogen to helium to carbon and on to heavier atoms, and stable atoms combine, in turn, to form molecules and macromolecules expressing "the potential stability that lay hidden in the primitive building blocks of cosmic hydrogen."(3) The sequence continues with the establishment and evolution of life forms, as stable atoms build the four base molecules (thymine, adenine, cytosine and guanine) which as stable configurations themselves are essential components for the formation of nucleic acids. Nucleic acids are the essential building blocks of genes, and so the process continues through the formation of the sub-units of proteins, to the proteins and on to the cells and to multi-cellular organism of increasing complexity.

The concept can be extended further still, since there is a definite sense in which social systems can be viewed as organizations generally dependent on, and historically related to, specific patterns of energy flow. This view becomes apparent when the technological aspects of society are studied emphasizing the available means and organization of essential metabolic support.(4) Similarly, local ecosystems and the biosphere as a whole can be regarded as energetically stable systems associated with specific food chains and with the broader aspects of mutually interdependent processes involving energy transformations.

The continuous sequence of steps that is implicit to the concept of stratified stability is normally divided by studies of evolution into three distinct phases broadly corresponding to evolutionary problems of a different kind. The first is the prebiotic "chemical" phase. The second is the phase dealing with the organization of matter into stable self-replicating entities and the transition from "non-living" to "living." The third phase involves the evolution of individual species.(5) Each phase in itself comprises a number of distinguishable stages and while all the specific mechanisms underlying the existence of each are not yet entirely understood, there is a basically similar logic applicable throughout. It relates to the idea of a succession of levels involving a progressive complexity, an increase in variability and the related emergence of novel properties.(6)

The third phase, in particular, involves a succession of stages which mark the ascent of living organisms and the evolution of a hierarchy of survival related mechanisms. These range from mechanisms associated with differentiation and the formation of specialized organs, to mechanisms such as those involved with sexual reproduction, the formation of nervous systems and complex brains and the development of various modes of perception and communication. They include social organizations of increasing complexity and lead ultimately to the rise of such properties as self-consciousness, logical reflection and moral judgment. From the view point of cybernetics, this succession is interpretable as manifesting an expansion in regulation capabilities (see Chapter 2), and living organisms, as they ascend the scale of complexity, show their ascent by a growing potency for regulating their environment under a greater range of conditions.

This view is implicit to Ashby's formulation of the cybernetic concept of regulation and its implications to the notion of adaptation. Two ideas emerge in this context as crucial. Firstly that in any complex dynamic system subject to the operation of unvarying constraints, some properties will be more resistant to change than others. These will tend to "survive" and gradually dominate their environment appearing as being particularly well adapted to its demands. If the total system is of an exceedingly high complexity, the selective processes leading to local stabilities will involve a wide range of dynamic activities rich in a variety of intriguing manifestations.(7) Complex as such activities may be, they are all traceable to the phenomenon of adaptation. In this sense, given the elaborate nature of the earth's surface, its age and the fact that it has been characterized by the operation of consistent constraints, then the evolution of dynamic self-preserving local stabilities (such as the existing forms of life) must be regarded as inevitable.(8)

Secondly, the active interactions of co-existing organizations (which are only partially autonomous in any case) continuously alter the properties of the medium in which they occur.(9) As initial constraints are modified, and with them the norms of "survival success," new needs and conditions for further evolution are being continuously established and the whole cumulative process proceeds with new possibilities and challenges created at each evolutionary step. The mutually adaptive processes that are inherent to the interaction of evolving organizations thus generate, as they unfold, the requirement for further adaptation. It is this feature in particular, which is interpretable by an observer as lending the evolutionary process its expansive qualities as well as its direction and logical continuity in time.

The idea that adaptation functions as the orienting factor, giving evolution the appearance of direction and "purpose," (10) obtains a specific functional meaning when it is subject to a cybernetic interpretation. The emphasis is on the close relation between the concepts of adaptation and regulation. From the cybernetic view point, the adaptive processes which underlie evolution are subject to the laws of control, specifically to the law of requisite variety and the possibility, in principle, of amplifying regulation. In so far as it reflects the requirements of such laws, selection in a dynamic environment will favor diversity, encouraging the formation of high variety regulators. This selective process works simultaneously on two distinct levels. On one level it operates to increase the regulation potential of specific organisms producing a better match between such organisms and the variety of their environment. On a higher, "meta-level", however, it operates not just by selecting particular organizations at random, but by encouraging variability in general. The result is an increase in the range and variety of adaptive possibilities, and a consistent general trend characterized by a succession of progressively more capable regulators.(11)

The succession of dynamic organizations which have emerged in the course of organic evolution can be clearly traced to the operation of such a consistent trend. The outcome has been the rise of forms showing a remarkable power to resist the unstabilizing effects of their dynamic environment. As Ashby points out, "they are resistant, not in the static and uninteresting way that a piece of granite, or a run-down clock, is resistant, but in the dynamic and much more interesting way of forming intricate dynamic systems around themselves (their so called 'bodies', with extensions such as nests and tools) so that the whole is homeostatic and self-preserving by active defense."(12)

The progression of increasingly more complex organizations which results is underlied by the operation of two essential mechanisms. One is the mechanism of self-regulation, or self-maintenance, expressed in the idea that organisms, at all levels of complexity, can be regarded as control systems with their own survival as the goal. (They are autopoietic systems in the sense of Maturana.) The other is the mechanism of evolutionary change which secures the attainment of self-regulation under variable conditions, allowing, through amplification, an increase in regulation possibilities. Social systems, like brains and other specialized mechanisms which have emerged as the products of evolution, can all be seen in this light as survival related tools. Their relative position on the evolutionary "ladder" is identified by successive increases of variability, and regulation effectiveness in an expanding niche.

The general trend of increasing variability, and hence, regulation potential, can be illustrated with respect to specific developments which mark major steps in evolution.(13) For example:

> The formation of multi-cellular colonies with functional differentiation and a division of labor, brought about a significant increase in the potential variety inherent to single cells.
>
> The development of the sexual mechanism of reproduction has affected a considerable increase in the range of genetic variation present in a given population. This increase is brought about by the constant reshuffling of genetic material during meiosis.
>
> On another level, this variety has been ensured and further increased by the cycle of birth and death and the mechanisms responsible for the alternation of generations. These mechanisms replace old organizations with fresh new ones, constantly opening the way for novel possibilities.

The evolution of learning as an adaptive mechanism made possible an increase in the finite amount of regulation exercised directly through the genes. By supplementing the information provided by the gene pattern with information reaching the organism from the environment, an ultimate amount of regulation can be achieved, far exceeding the original capacity inherent to the genes alone.(14)

In relation to the above, the development of complex brains and particularly of intelligence produced a definite advantage over simple forms of instinctive behavior, by elaborating the working of response mechanisms, providing the possibility of choice between alternative actions, and generally increasing the range of behavioral options.

A striking increase in survival advantage has been brought about by the development of socialization and of ever more effective modes of communication. In the most obvious sense, socialization and coalition formation make joint efforts possible which far exceed the capabilities inherent to individual organisms.

The examples given above illustrate the evolutionary trend of increasing variability in general. From a more specific "functional" view point, increases in regulation capabilities have been achieved through the elaboration and constant perfection of mechanisms of perception, mechanisms of computation, selection and communication, mechanisms with which an organism could increase the range of its operations and the possibilities of actively effecting its environment, and ultimately through the continuous integration of all these, into viable stable organizations.

Gains in capacity, efficiency and potentiality of self-regulation achieved during the course of biological evolution, have been expanded many folds with the emergence of human social systems and the more recent development of civilization. (15) In social systems, underlying biological regulation capacity has been amplified by two fundamental "inventions." One is the development of language the high versatility of which made possible the generation, accumulation and communication of highly complex information, rendering personal knowledge and individual experience easily transferable within and across generations. (16) The other is the development of technology and of specialized tools, which brought about a tremendous extension in the range and capabilities of vital organs. Technology and the essentially symbolic nature of regulatory social processes have cumulatively extended the limits inherent to physical mechanisms of biological orgins. They have resulted in a comprehensive survival advantage which has ultimately replaced adaptation by direct selection of genetic variants with a far more efficient method.

Social systems integrate single humans into super-individual organizations sharing augmented physical resources and a collective "mind." Nevertheless, within the social organization, the carriers of cognition, volition and consciousness are individual human beings who, through their unique insights, experience, capabilities and drive, can contribute to shaping the course of evolution itself.

4-2. The Dynamics of Stability in Social Systems

Social systems are evolving organizations.(17) As such, they belong to a class of systems sharing a common type of underlying processes and an invariance in particular organizational aspects which 1) make possible adaptive modifications of structure and function in response to environmental changes and 2) allow for improvements in the mechanisms through which such adaptive modifications are achieved. The common features appear on a level of abstraction stressing the principles of reproduction, variation and selection (applicable to competing and/or cooperating organizations), although domains in which such principles find their expression differ greatly in appearance, in behavior and in the specific fabric by which they are sustained. The special peculiarities of mechanisms mediating evolution in such different domains may obscure the invariant characteristics, which nevertheless are central to the logic of evolution in animals, machines, cognitive processes and sociocultural systems.

In particular, the similarity between the evolution of concepts in brains (or groups of brains) and the evolutionary processes occurring in sociocultural systems has been pointed out.(18) This similarity goes beyond a simple analogy since in social systems, as in brains, regulation is affect by processes which are essentially symbolic in nature. In both cases, such regulatory processes can be represented by organizations of specific classes of goal-directed programs involving various modes of computation and including, for example, the possibility for prediction (as in the model offered by Fogel, Owens and Walsh) and resolution of undecidable situations (as in Eve-1).

Moreover, there is a definite sense in which a social system can be regarded as a "brain," computing and bringing about the near optimal relations which maintain its (the social) overall stability. Individual human brains, together with their mechanical extensions, function as the computational elements in such a macro-brain, and the classes of programs they run are temporarily subservient to the "externalized" macro-programs integrating the social purpose and regulating social goals. (These are manifest in conventions and traditions, rules, mores, rituals and the like.) Single brains are essential, however, for the process of evolution since they provide the source of required variety by generating new concepts, articulating a new purpose and rejecting established norms.

A social system can thus be identified with a named class (or classes) of goal-directed programs,(19) executed in a particular kind of hierarchical organizations (see section D-9 in Appendix D) where they can be reproduced and, under certain conditions, evolve. Selection among competing and cooperating programs is typical to the evolutionary process, cooperation being particularly important in psychological and social systems. The simulated processes mediated by the execution of Eve-1 (see Chapter 3) portray the role of cooperative behavior in the evolutionary process and emphasize a more general characteristic of evolution, namely, that under certain "undecidable" situations evolutionary change becomes essential. An undecidable situation is interpretable as resulting from a modification in the conditions underlying a system's interaction with an environment. If such a modification exceeds the system's repertoire of adaptive responses, the range of tolerance which is compatible with its survival (as defined by its "essential variables") will be threatened. Ultimately, the system will either perish, or, by expanding its repertoire of survival related options, it will evolve.

The cogency of the evolutionary processes simulated by Eve-1 can be enhanced with respect to a societal interpretation if we allow: 1) that properties of simple automata stand for classes of goal-directed programs, 2) that such programs are embodied in adaptive controllers like Pask's unit of control or the TOTE unit of Miller, Galanter and Pribram (see sections D-6 and D-8 in Appendix D) and 3) that such units of control can be made to represent regulatory processes of arbitrary complexity when they are organized in configurations reducible to sequences and hierarchies of TOTE units such that the whole organization is a TOTE unit itself.

A redundancy of mechanisms is inherent to such an organization, where the task of computation is distributed over a large number of components involved now in one computational activity, now in another. This property is essential for representing the dynamics of sociocultural processes since, in reality, the programs by which such processes are mediated, are run in a large number of different brains and in various artifacts, all interacting in a complex manner such that precise identification or localization is made impossible. In addition, the hierarchy employed in such organizations allows for self-referential capabilities. These interpret current states of computation in the system's components and are an essential condition for evolution.(20) In a more specific vein, evolution will occur under "crisis" conditions, for example, when a conflicting situation develops due to concurrent computation of incompatible programs, or due to conflicts between "internal" and "external" goals. In such cases resolution will require appropriate modifications in existing programs, or the production and integration of new programs in a more comprehensive repertoire.

The concept of a "conversational" interaction and the constructs employed by Pask to represent the dynamics of cognitive processes and learning (see section D-9 in Appendix D with the related references) are applicable to a representation of sociocultural evolution. The correspondence is important,(21) and since we are concerned with enhancing the societal interpretation of evolutionary processes embodied in Eve-1 - a far simpler model - some additional comments are crucial.

Firstly, while social processes can be imaged as programs embodied in, and executed by, TOTE like organizations, they cannot be performed (simulated) by such. The intricate web of interactions which mediate social stability and underlie social evolution is not constrained by seriality. In reality it involves many concurrent events, and the concept of concurrent computation (22) is therefore essential. Next, in a concurrent processor, computations in initially asynchronized centers of control may become synchronized due to cooperative interactions. Synchrony is brought about by means of information transfer (23) and it is interpretable as a conflict-resolving interaction. As a result, an evolutionary process will be manifest in the development of dependencies among initially independent loci of computations. Finally, the development of such dependencies is analogous to an increase of coupling between components (single automata) and their integration into a new "larger" system. The latter may be, or may not be more efficient than earlier configurations. Here judgment can be made only in retrospect, after pertinent selection processes have had their effect.

With the ideas discussed above in mind, a simple model can be used as a means for highlighting the major cybernetic features which underlie the dynamics of stability (or instability) in social systems. The model is, of course, a gross simplification of the intricate social reality and the complexity inherent to the social fabric. As such, it is likely to be accused of major omissions. It is therefore important to stress that it is not intended for representing a detailed model of a social system. Rather, its utility is in providing a simple representation, which as a conceptual construct, can assist the discussion of mechanisms underlying stability and change in social systems. It can also be useful for the purpose of identification, providing a bridge between some of the abstract ideas discussed earlier and more familiar aspects characterizing social processes. In particular, it can make a historical interpretation easier.

The model is depicted by Figure 25 below, where the emphasis is as a "homeostat" like organization. It is conceived on a low resolution level which glosses over the complex interactions within each major component and between them. Nevertheless, it preserves the operational logic underlying the organization of the processes involved. The complexity of such processes can be imaged by elaborate constructs of interacting TOTE like units with the important provisions discussed above. Much as the case of the brain (when it is studied from the cybernetician's viewpoint), the actual complexity characterizing the working of society defies a detailed tracking. It must be kept in mind, however, as some global features are discussed.

The view taken here is that the aggregate behavior of a social system (as it appears to an external observer) is conditioned by the dynamic interplay of a number of critical factors which all together shape the broad characteristics of a social system at a given time. Problems of social stability can be interpreted with respect to the interaction of such factors, and social evolution can be seen in the light of changes in their constitution, and in their continuous integration into a succession of stable and increasingly more complex systems. These, coincide with major historical transition which have marked the social evolution of mankind.

The critical factors shaping the characteristics of a social system include the following:

- the biological make-up of humans.
- the characteristics of a particular geographical environment.
- the available technology.
- the symbolic representation of the world that is employed.
- the value system shared by members of a social group.
- the institutional organization underlying a social order.

In the model, these factors are grouped into four major domains

(24) which are defined as follows:

1) The physical domain: represents the total local eco-system (as in the Tsembaga), including the biological make-up of humans and the man-made part of the environment (technology). The environmental component of the physical domain conditions the requirements for adaptation, in the general sense that the terrestrial environment favors particular organizations and in the more specific sense that particular geographical characterisitcs determine specific adaptive needs. (25)

2) The conceptual domain: represents the available model of the physical domain. It includes scientific models which are particularly effective for manipulative purposes, but also a host of other less rigorous (and even scientifically incorrect) concepts. All together, it constitutes a "world-image" which is shared by members of a social group and is passed on by education. This image is embodied in procedures which guide social action. The actual effectiveness of such actions depends to a great extent, on the accuracy and refinement of the models employed. In this sense, the conceptual domain represents not only the realm of "what is known," but ultimately also the boundaries of "what is potentially possible." (E.g. for a successful journey to the moon, an effective model of celestial mechanics is imperative.)

3) The ethical domain: represents the value system shared by members of a social group. It provides a normative framework defining both the "acceptable" and the "expected." The moral imperative and concepts of right or wrong which are inherent to a value system condition the choice as well as the priorities for action. They play a dominant role in the articulation of social goals and in specifying the nature of relations among humans, and between them and their environment.(26) Like the world image, a value system is passed on by education as well as by less formal means of social conditioning. (Values are implicit to mythologies, folklore, songs and stories to which children are exposed, etc.)

4) The organizational domain: Social actions (in the broadest sense) are carried out through an organizational framework which specified procedures for decisions and actions and provide an organized means for carrying these out. The organizational framework is embodied in the structure of institutions, including various forms of government, systems of law, economic systems and the like. These may vary greatly in respective rigidity, scope and other characteristics, but they all share (in principle) a common adaptive function - that of organizing actions for a common survival advantage.

The sharp distinction between the four domains is arbitrary. In reality, they overlap to the extent that an absolute and clear separation is quite impossible. In a similar vein, their mutual interaction does not occur through single channels (as indicated by the two directional arrows in the diagrams), but through a web-like structure tying together the many processes involved. The whole constitutes a complex fabric of loci of events (control) and "threads" of informa-

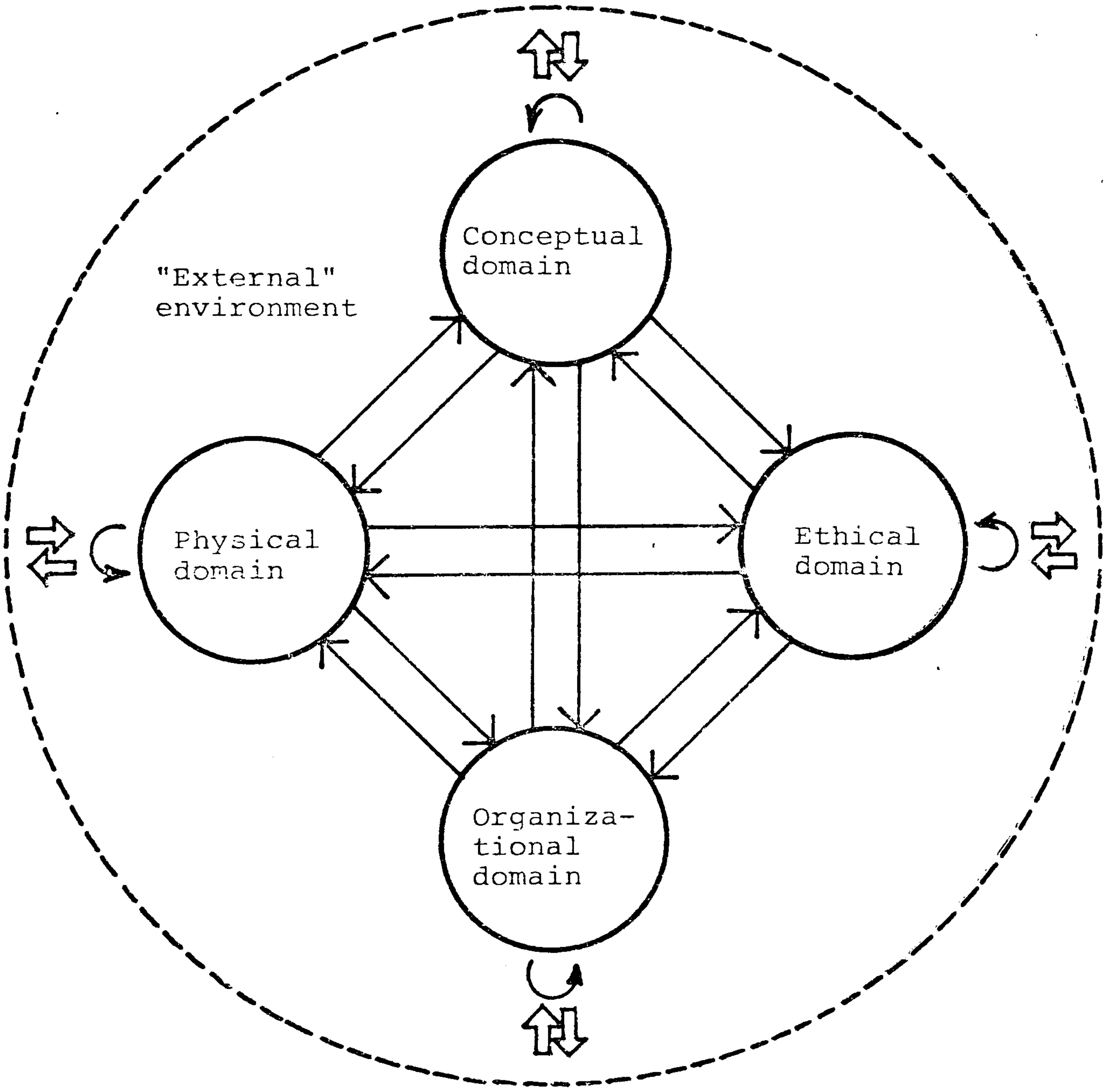


Figure 25. The Dynamics of Social Stability - Major Domains of Interaction.

tional coupling. The definitions of domains as separate entities is employed for a descriptive convenience and the arrows are used in order to symbolize mutual dependencies.

The diagram represents a dynamic structure reducible to processes involving complex mutual interactions that are circular and non-serial in nature. Each domain is affected by the state of every other, while the state of each, and the interaction of all, represent the constraints (or potentials, depending on the point of view) which are ultimately manifest in the global condition of a social system. The whole can best be interpreted with respect to an iterative sequence of "challenges and responses" in Toynbee's sense.(27) This sequence is characterized by steps of related cumulative changes, whereby modification of states in one domain affect a corresponding change in the others. Such changes are regulated by a matching process (28) through which their effects are being continuously synchronized.

From a historical perspective this translates into a view which sees the challenges of a particular environment met by an integrated set of adaptive responses embodied in a specific technology, a specific mode of social organization, a communally shared symbolic representation of the facts of experience and a system of values. These factors have always been intimately related and the particular characteristics of each has affected and has been reflected in the characteristics of the others. Their interaction has involved the application of mutual constraints inhibiting particular developments at one time while reinforcing and accelerating other developments at another.(29)

In a stable social system these aspects are compatible, their interactions are synchronized and their respective manifestations consistent. This condition of stability is interpretable as a match of varieties in the sense of the theory of regulation and it is displayed by well adapted societies, such as the Tsembaga (see Chapt. 1). An unstable situation, on the other hand, would result from internal inconsistencies, mismatching situations and conflicts between states of the four domains. Such instabilities may cause ultimate disintegration, but under certain circumstances they may also stimulate evolution, which through a meta-process of conflict resolution could bring about a new level of sytemic integration.(30)

The steady state which characterizes the Tsembaga as a viable system represents a special case of stability which is the exception rather than the rule. Most societies in history, if they did not perish, were forced to continuously readapt and evolve. In the related process of social change two major sources of variety have played an important role. One is a source of potential variety inherent to the complexity of the system itself. (Represented in the diagram by circular arrows originating and returning to each domain.) This "internal" source of variety could generate a spontaneous activity which would spread through the whole system as it searches for a new equilibrium.

More significant to social evolution have been external sources of variety. These are implicit to the idea that specific societies and their ecologies constitute a part of a larger "external" environment (broken circle encompassing the four domains in the diagram), in which other conditions prevail and other societies exist. Throughout history, exposure to such external sources of variety have involved territorial expansions (a change of environment) as well as contacts between social groups and whole civilizations, with a resulting exchange of knowledge, transfer of technology, adoption of new values and a diffusion of forms of institutional organization.

Such occasions require a process of adaptation and a synchronization of the new situations, affected in the manner already discussed above. A typical example is offered by the Cargo Cultures studied by Ted Schwartz in New-Guinea.(31) These have emerged as a result of an encounter between a stable local society and Western Civilization. The rise of masseianic movements which have followed this encounter, and the associated violent "internal" upheaval, can be regarded as a pathology. But it can also be interpreted as a process by which such a local society, drawing upon the resources of its internal variety, generates a sudden and dynamic activity as it seeks for a new stability and a new level of integration. A new stable equilibrium is not always assured. If the inherent potential for variability proves insufficient, the conflicting circumstances may not be resolved. At times, it can lead to a genuine impasse and a "Double Bind" situation in Bateson's sense.(32)

A viable social system is an ultrastable system. But unlike Ashby's mechanical "Homeostat," its environment does not represent only a source of disturbances. It also provides a source of potential linkages which are formed when the system "expands" as it gains control over its environment. This expansive quality has been a dominant characteristic of the dynamic process of interaction between man and his environment and the emergence and evolution of civilization. It followed "spiralling" pattern of self-reinforcing events in which a new technology,developed in response to a perceived challenge, has invariably lead to a growing awareness of a larger and more inclusive environment, which by presenting new problems forced the development of further technology, which in turn has further increased the scope of man's world, and so on. Each such step was followed by an increase in knowledge (thus anticipating the next step), and each has involved changes in organizational requirements as well as in the accepted notions of right and wrong. Signalling the major historical transitions which have characterized the evolution of human society, such changes have been accumulating continuously until, repeatedly, a critical stage had been reached where their integration has brought about a significant qualitative transformation and a new phase in human affairs.

In particular such qualitative transitions have been typical to the Neolitic, the Urban and the Industrial "revolutions."(33) Each such transition has been characterized by specific environmental circumstances,(34) a particular technology, a "level" of knowledge of the world, a typical form of organization and a system of values.(35) In each case these aspects constitute a coherent whole which makes the historical distinction possible. If one subscribes to an optimistic view of history and the idea of "progress," such transitions describe a trajectory of an ever-increasing human advantage, manifest, for example (and in spite of many temporary setbacks), in a continuous increase in longevity, a consistent expansion of degrees of freedom and a persistent pursuit of individual liberty. But each such historical transition has brought with it many new problems without guaranteeing the promise of continuous "success."

4.3 Reflections on Some Implications

> "The cities are narrow and so are men's minds. Superstition and plague. But now we say: because it is so, it will not remain so. For everything moves, my boy."
>
> Bertolt Brecht
> The Life of Galileo

Following the industrial revolution an unprecedented acceleration in the development of science and technology has brought about swift and far-reaching changes in man's relation to nature. Such changes are manifest in new and overwhelming problems which make the possibility of a total self-destruction a real threat, but they also suggest the feasibility of a new phase in human existence, whereby in a world free from material want, the creative potential inherent to societies and individual humans could be realized on a scale never known before.

The most critical aspects of the recent change in circumstances underlying mankind's existence, relate to the magnitude of potential impacts of human activities on the total biosphere and to the rate of change itself. The impact of human activities, which had previously been locally containable, is now global in nature affecting almost every part of the terrestrial environment. The rate of change has accelerated within the last century to a point which makes the cumulative changes in all previous history look painfully slow.(36) Both the magnitude and the rate of change have far exceeded the adaptive capacity of existing organizations as well as their ability to manage human affairs in a stable manner.

The results are all around us. They are manifest in economic, political, social and ecological instabilities which haunt our technological civilization and threaten the likelihood of its continuous existence. From the viewpoint of the discussion in section 4.2 above, such instabilities are interpretable as being symptoms of maladaptation between conditions characterizing the states of the four interacting domains. They result from internal inconsistencies, mismatching situations and conflicts between new perceptions, knowledge, problems and possibilities, and archaic ethics, outmoded concepts of organization and outdated institutions.

The point is this, systems of values and forms of organizations employed at present have evolved in the past where adaptive changes could be slow and spread over millenia. They are entirely inadequate for the high rate of change which characterizes the human environment at present, requiring a great deal of "flexibility," fluidity in structure and rapid adaptation. Furthermore, as mechanisms which are ultimately responsible for regulating the social stability, they have emerged in a past where relative isolation of human groups, scarcity and fierce competition for meager resources were the most fundamental condition. They are therefore entirely unsuitable for a potential economy of abundance in a world that has shrunk so fast as to make all significant human activities interdependent, rendering the concept of isolated and antagonistic nation states utterly obsolete.

These are but some of the factors which will require transformations in concepts, ethics and organizational structures as essential and profound as those which have accompanied, for example, the transition from a hunter's to an agrarian way of life. But such transformations will have to be accomplished in a much shorter span of time than was available in earlier periods, and they will have to be accomplished with the conscious, well-informed and active participation of all humans who inhabit the earth. Szent-Gyorgyi has expressed the need for such a major adaptation succinctly:

> "Here we stand now, on our tragically shrunken globe, with our ruined economy, with these terrific weapons in our hand, fear and distrust in our hearts.
>
> We either adapt to the new situation, revamp our thinking and human relations, exchange our outdated ideas of glory, force, domination and exploitation for mutual understanding, respect, help and collaboration, or else perish."(37)

Mankind is at a turning point.(38) An "undecidable" situation which not unlike the evolutionary dilemmas parodied by the activities of simple automata in Eve-1, will require a major adaptive restructuring and a new integration of human affairs on a vast and more comprehensive scope. The inexorable condition for such a new integration demands the unification of human activities on a global scale, this, not only with respect to technological, economic and ecological considerations but almost in every facet of life, extending man's internal organization to include his technology, his institutions and total ecology into a single stable self-organizing system, conducive to evolution and the pursuit of excellence.

The problems involved in such an integration are all but simple. The uncertainties that are inherent to the evolutionary process make planning it (in the strict sense) quite impractical. Nevertheless, the system can be encouraged to evolve. In this, cybernetics can offer some profound insights since it provides important notions as to how evolutionary behavior may be catalyzed. Two concepts in particular are crucial. Firstly, that any behavior depends on an underlying mechanism and it is therefore constrained by a particular organization and its specific structure. For an expansion in behavioral possibilities to occur, related expansions in underlying organizations must be made possible. Secondly, that a potential variability, and a redundancy of mechanisms with the associated decentralized/distributed control, are essential to the innate dynamics of mutualism which promotes evolution. For society, this means a need for a complete revision of the concept of power so that a vast potential of creativity can be tapped with the true "human use of human beings."

The requirement for variability and the notion of distributed control imply an "untidiness" which characterizes the fluidity of life and its persistent imperfections. These may offend a simple-minded concept of order, authority and permanence but they are essential for sustaining evolution. As planners, philosophers, educators, managers and others approach the problem of planning for change and for social as well as individual self-realization, these requirements must be taken into account;(39) recalling with humor, if not with awe, that ultimately, there are more things in heaven and earth than are dreamt of in Horatio's (40) philosophy...

NOTES

1. HOMEOSTASIS AND STEADY STATE REGULATION IN A WELL ADAPTED SOCIETY

1. For a state determined behavior, where a succession of states can be described by a trajectory in a phase space, a condition of equilibrium is manifest by lines converging into a point or entering a closed loop showing evidence of a cyclical activity. A condition of multiple equilibria is represented by a stable region in the phase space, and a behavior will be equilibrial as long as its representative points (trajectories) are not carried outside the stable region. (See Ashby, Ref. 2 below.)

2. For a detailed discussion on stability and equilibrium, see Ashby, W. R., An Introduction to Cybernetics, as well as Design for a Brain.

3. See von Foerster, H., "Basic Concepts of Homeostasis." BCL publication No. 5 reproduced from Homeostatic Mechanisms, Brookhaven Symposia in Biology: No. 10 (1957); pp. 216-242.

4. Ibid., p. 237, but see the rest for a detailed argument.

5. Cannon, W. B., The Wisdom of the Body (first published in 1937).

6. See McCulloch, W., "Finality and Form in Nervous Activity" in McCulloch, Embodiments of Mind, pp. 256-275.

7. Quoted by Cannon, The Wisdom of the Body, p. 38.

8. Ibid., p. 24. In Cannon's own words: "The coordinated physiological processes which maintain most of the steady states in the organism are so complex and so peculiar to living beings--involving, as they may, the brain and nerves, the heart, lungs, kidneys and spleen, all working cooperatively--that I have suggested a special designation for these states, homeostasis."

9. See von Foerster, H., "Basic Concepts of Homeostasis," BCL publication No. 5.

10. See Cannon, W. B., The Wisdom of the Body.

11. Some such physiological mechanisms operate by lowering or increasing the speed of continuous processes and others function by causing the storage or release of specific chemical substances. Some involve direct physico-chemical regulation only, others are controlled by the autonomic systems and yet others by the central nervous system. In addition to Cannon, see Klir, J., and Valach, M., Cybernetic Modelling, p. 221.

12. Cannon, W. B., The Wisdom of the Body, p. 303.

13. Goldman, S., "Further Considerations of Cybernetic Aspects of Homeostasis" in Self-Organizing Systems, Yovits & Cameron, eds., pp. 108-120.

14. Cannon, too, emphasized the fact that many bodily structures compromise economy for the sake of redundancy in order to ensure an adequate margin of safety. In this context it should be mentioned that the concept of redundancy has received a rigorous treatment by information theory. For the general treatment, see Shannon, C., and Weaver, W., *The Mathematical Theory of Communication*. For the treatment of the subject with respect to reliability (in the context of computation), see Von Neuman, J., "Probablistic Logic and the Synthesis of Reliable Organisms from Unreliable Components," *Automata Studies*, Princeton University Press (1956).

15. Ashby combined ideas similar to those proposed by Sommerhoff with set-theoretic methods developed by the Bourbaki school to produce a general definition of homeostatic regulation. See Ashby, R. W., "The Set Theory of Mechanism and Homeostasis," Tech. Report No. 9, Electrical Engineering Research Laboratory, University of Illinois, Urbana (1962).

16. The set theoretic formulation relates a set D of disturbances (d) to a set E of environmental states (e) and a set F of states (f) assumed by a regulator. The relation D-E is specified by a mapping ϕ of D into E, and the relation D-F is specified by a mapping ρ of D into F. The relation E-F of states (e) assumed by the environment and states (f) assumed by the regulator define uniquely a set of outcomes Z. This relation is given as a mapping ψ of E x F into Z. The

crucial idea is that Z, the set of all possible outcomes, contains a subset G of those particular outcomes which correspond to the value of a system's essential variables. Homeostasis is achieved when regulation is exercised such "that ρ is so matched to ϕ and ψ that goal G is arrived at even after displacement from it." See ref. 15, pp. 30-33 and p. 42.

This formulation is general in that the relations specified are entirely independent of a system's specific fabric. Depending on special cases, the set G, corresponding to the values of the essential variables, will be of a physiological, socio-economic, or any other nature.

17. Ashby, W. R., Design for a Brain, especially Chapter 5.

18. Ibid., p. 64.

19. Ibid., p. 84. What would otherwise be a random process of trial and error is in fact conditioned by previous history of successes and failures.

20. Beer, S., Brain of the Firm, p. 38.

21. See Pask, G., in An Approach to Cybernetics.

22. See Ashby, Design for a Brain, especially Chapters 6-9. The principles involved are embodied in a mechanical device, the "Homeostat," which exhibits ultrastable behavior.

23. Typical material can be found in references 80, 86, 88, 93 and 94 of Appendix C.

24. Lerner, I. M., Genetic Homeostasis. But see in this connection also Penrose, L. S., "The Supposed Threat of Declining Intelligence," Am. J. Mental Deficiency, 53,(1948); pp. 114-118.

25. Jung, C. G., Modern Man in Search of Soul, p. 17. But also Craik, K., The Nature of Psychology edited by Sherwood, S., for a view which stresses the regulatory features of human psychology.

26. Wiener, N., Cybernetics, see pp. 160-161.

27. See for example Bateson, G., "Epilogue 1958," in Naven. Also various discussions and Prologue in Bateson, C., Our Own Metaphor.

28. Wilkins, L., Social Deviance.

29. Rappaport, R., Pigs for the Ancestors.

30. See Beer, S., "Towards a Cybernetic Factory" in Principles of Self-Organization, von Foerster and Zope (eds.), pp. 25-80. Also Brain of the Firm, and other writings.

31. Wynne-Edwards, W. C., Animal Dispersion in Relation to Social Behavior.

32. Slobodkin, L. B., "Animal Populations and Ecologies," in Positive Feedback, J. H. Milsum, ed., pp. 149-163.

33. In the following sections, Rappaport's study of the Tsembaga will be used to illustrate the condition of homeostatic stability in a well-adapted society. The account is based entirely on Rappaport's work, his material, data, and interpretation of the regulatory function of rituals. It is hoped that no violation is done in the short presentation that follows to his excellent work.

34. The following is intended only to give a flavor of some major features which characterize the Tsembaga and their environment. The sources are Chapters 1-4 in Rappaport's Pigs for the Ancestors and the original material should be consulted for further details.

35. Ibid., p. 59.

36. Rappaport makes a distinction between the local ecosystem and the regional system. The former is defined essentially as a system of localized trophic exchanges while the latter provides the contest in which distinct human populations interact through the exchange of goods, personnel, and genetic material. A local population such as the Tsembaga participates in both systems.

37. The Australian government has acted to pacify the region and the diagram is written to express conditions as they existed at earlier times.

38. For the purpose of his study, Rappaport made use of the following formula for computing the carrying capacity:

$$P = \frac{\frac{T}{(R+Y)} \times Y}{A}$$

"Where:

P = the population that can be supported

T = total arable land

R = length of fallow in years

Y = length of cropping period in years

A = the area of cultivated land required to provide an 'average individual' with the amount of food that he ordinarily derives from cultivated plants per year."

See _Pigs for Ancestors_, pp. 92-96.

39. As Rappaport points out, a similar effect is achieved by the Kaiko during which trade activity is facilitated to a great extent. See pp. 190-191.

40. In this respect see also Goldman, S., "Further Consideration of Cybernetic Aspects of Homeostasis," especially p. 116.

41. See Appendix D, especially sections D-3, D-5 and D-6.

42. See for example p. 240 in Rappaport's Pigs for the Ancestors.

43. Pask refers to such a program that was written to represent the ritual cycle. See p. 98 in Pask, G., The Cybernetics of Human Learning and Performance. The actual reference is given as Cartledge, J. W., and Rejac, G. L. (1970), "Simulation of the Tsembaga Ritual Cycle," Term Thesis I.C. 5626, School of Information Sciences, Georgia Institute of Technology.

44. On this problem of the integrative function of regulation see Claude Levi-Strauss Totemism, for an example see p. 70.

45. Bronowski, J., The Ascent of Man, see p. 131.

46. This condition is quite typical to traditional societies for which Margaret Mead has coined the expression "postfigurative cultures." See Mead, M., Culture and Commitment.

2. AMPLIFYING REGULATION AND VARIETY INCREASE IN EVOLVING SYSTEMS

1. The notion of an essential interplay between constancy and change can be approached from different viewpoints. Thus, Ashby, for example, points out that change in some variables of a system is essential for maintaining the constancy of others. See Ashby, W. R., Design for a Brain.
On another level, Bronowski has stressed the significance of error in molecular reproduction for the process of evolution. Here in particular, an appropriate balance between constancy and change must be maintained since both extremes, of excessive modification or a rigid constancy, can lead to a system's breakdown. See Bronowski, J., "New Concepts in the Evolution of Complexity: Stratified Stability and Unbounded Plans," in Zygon, Vol. 5 (1), (1970); pp. 18-35.

2. Maturana, for example, coined the term "Autopoiesis" to describe a particular kind of dynamic constancy that is typical to living organizations. The "autopoietic" organization is defined as a unity by a network of processes of production of components, characterized by a fundamental circularity, whereby the product of the network's operations is that network itself.

Autopoiesis is thus a special case of homeostasis in which the essential variable that is maintained constant is a system's own organization. The concept implies a self-realizing unity by which the autonomy of the system is defined. The establishment of such a unity and its constancy, Maturana points out, is a logical and operational prerequisite for reproduction and evolution.

See Maturana, H. R., "Neurophysiology of Cognition," in _Cognition: A Multiple View_, Garvin, P., ed., pp. 3-23. Also Varela, F. G., Maturana, H. R., and Uribe, R., "Autopoiesis: The Organization of Living Systems, its Characterization and a Model," in _Biosystems_, 5, (1974); pp. 187-196.

3. See Slobodkin, L. B., "Animal Populations and Ecologies," in _Positive Feedback_, Milsum, J. H., ed., pp. 149-163.

4. Beer, S., _Decision and Control_.

5. Pask, G., "A Cybernetic Model for Some Types of Learning and Mentation," in _Cybernetic Problems in Bionics_, Oestereicher, M. C., and Moore, D. R., eds., pp. 531-585.

6. The formulation relates to the idea of a self-reproducing machine that is not limited to making precise replicas only. For the basic argument see Von Neumann, J., _Theory of Self-Reproducing Automata_, Burks, A., ed. But also:
Von Foerster, H., "Molecular Ethology," in _Molecular Mechanisms of Memory and Learning_, Ungar, C., ed.;
Loefgren, L., "Relative Explanation of Systems," in _Trends in General Systems Theory_, Klir, G., ed.; Myhill, J., "The Abstract

Theory of Self-Reproduction," in Essays on Cellular Automata, Burks, A. W., ed., pp. 206-218.

7. For a full discussion see Pask, G., An Approach to Cybernetics, also Pask, "The Cybernetics of Evolutionary Processes and Self-Organizing Systems," Proc. 3rd Cong. Int. Assoc. of Cybernetics, Namur. Gauthier Villars ed., (1965); pp. 27-75.

8. Pask, G., "The Cybernetics of Evolutionary Processes and Self-Organizing Systems," p. 39.

9. See, for example, Teilhard de Chardin, P., The Phenomenon of Man, also by the same author, The Future of Man.

10. For example, Glansdorf, P., and Prigogine, I., Thermodynamic Theory of Structure, Stability and Fluctuations. For additional references see notes No. 64 & 65 to Appendix C.

11. See chapter 15 in reference No. 10 above. For additional examples see also:

Prigogine, I., "Structure, Dissipation and Life," in Theoretical Physics and Biology: Proceedings, Marois, M., ed., (1969) pp. 23-52.

Katchalsky, A., and Kedem, O., "Thermodynamics of Flow Processes in Biological Systems," in Biophysical Journal, Vol. 2, No. 2, (1962); pp. 53-78. as well as:

Katchalsky, A., "Thermodynamics of Flow and Biological Organizations," in Zygon, Vol. 6, (2), (1971); pp. 99-125.

12. See concluding remarks in Katchalsky, A., "Thermodynamics of Flow and Biological Organization." But especially see Jantsch, E., Design for Evolution.

13. The formulation offered by non-equilibrium thermodynamics removes earlier difficulties concerning the seeming conflict of the idea of evolution in biology and the second law of thermodynamics. Prigogine has resolved these difficulties by showing that the seemingly contrasting concepts, relate to different thermodynamic situations - near and far from equilibrium - both of which are subject to one physical law. For example: "Broadly speaking destruction of structure is the situation which occurs in the neighborhood of thermodynamic equilibrium. On the contrary, creation of structure may occur, with specific non linear kinetic laws beyond the stability limit of the thermodynamic branch..." Glansdorf, P., and Prigogine, I., Thermodynamic Theory of Structure, Stability and Fluctuations, p. 288.

A particularly significant contribution to the unification of concepts of evolution, going beyond the scope of present irreversible thermodynamics, is offered by Eigen who introduced information theoretic concepts to a treatment of the problem of evolution. Eigen has emphasized the idea that the use of information associated with a high "selective value," rather than an economization in the consumption of free energy, is the crucial factor in evolution. See Eigen, M., "Self Organization of Matter and the Evolution of Biological Macromolecules," in Die Naturwissenschaften, 58, (1971); pp. 465-523.

14. See Bronowski, J., "New Concepts in the Evolution of Complexity: Stratified Stability and Unbounded Plans."

15. See Sommerhoff, G., Analytical Biology, and Ashby, R. W., Introduction to Cybernetics.

16. See Conant, R. C., and Ashby, R. W., "Every Good Regulator of a System Must be a Model of that System," Int. J. Systems Sci. Vol. 1, No. 2, (1970); pp. 89-97. For the development of the set theoretic formulation see Ashby, R. W., "The Set Theory of Mechanisms and Homeostasis," Tech. Report No. 9, Elect. Engin. Research Lab. Univ. of Ill., Urbana, (1962).

17. Ashby, R.W., "Requisite Variety and its Applications for the Control of Complex Systems," in Cybernetica, Vol. 1, No. 2, (1958); pp. 53-99.

18. Ashby, R. W., Introduction to Cybernetics.

19. See Conant, R. C., "Information Transfer in Complex Systems, with Application to Regulation." Tech. Report No. 13. Biological Computer Laboratory, Univ. of Ill., Urbana, (1968).

20. For a discussion of such various schemes and their symbolic representation see Ashby, R. W., Introduction to Cybernetics. For a quantitative discussion see Conant, R. C., "Information Transfer in Complex Systems,with Application to Regulation." Also Conant, R. C., "The Information Transfer Required in Regulatory Processes," in IEEE Trans. Systems Sci. and Cybernetics, Vol. 5, No. 4, (1969); pp. 334-338.

21. The law of requisite variety can be deduced from the game theoretic formulation in which a set D of disturbances d_i is countered by a set R of responses r_j producing a table with values z_{ij} of the outcomes Z at the intersections. By selecting a move d_i, D selects a particular row in the table. Following D's move, R selects a value r_j and thus a particular column.

In a table of this kind, with r rows and c columns, where no element in a column is repeated, and where R acts to reduce the variety in the outcomes Z, there is a quantitative relation between the varieties of D, R and Z. As Ashby has shown, the variety in the outcome cannot be less than the value of r/c. Consequently, for a given variety of D, Z's variety can be reduced only by a corresponding increase in the variety of R.

See Ashby, W. R., Introduction to Cybernetics.

22. Ibid, p. 211

Ashby has shown that the concept of regulation as a process in which a stability is maintained in spite of a stream of disturbances is homologous with the information theoretic concept of correcting for noise in a transmission channel. The law of requisite variety relates closely, therefore, to Shannon's theorem (No. 10) which states that the quantity of noise which can be removed from a message is limited by the quantity of information which can be carried by a correction channel.

23. For a discussion of the significance of constraints in the structure of an environment to the problem of regulation, see Ashby, R. W., An Introduction to Cybernetics, also Ashby, "What is an Intelligent Machine," BCL Publication No. 44, Univ. of Ill., Urbana, and Ashby, "Design for an Intelligence-Amplifier," Automata Studies, Shannon C. E., & McCarthy J., eds., (1956); pp. 215-234.

24. Ashby's concept of ultrastability, especially as it is embodied in his "Homeostat," relies on the idea of a system containing a sufficiently large internal variety, the latter allowing for new combinations and recombinations of internal states in a search for stability that is synchronized with unpredictable variations in perturbations. As it stands, the concept can not account for the increase in complexity that is typical to evolution. Here we must allow for incorporating

new variety from external sources (selected parts of the environment) in a process that is subject to the same general selection criteria for stable configurations. Selection is now applied to new entities in which systems, previously perceived as individuals, combine into super individual units yielding a specific "survival" advantage.

3. Eve-1: A Simulated Ecology With Some Characteristics of Evolutionary Processes

1. A comprehensive review of the relevant bulk of work must remain outside the scope of the present chapter. A list of representative references can be found in the appendix to Pask's "Cognitive Systems," (a paper prepared for a symposium on "Cognitive Studies and Artificial Intelligence Research," The University of Chicago, March 1969). Pask's list is greatly augmented by Minsky's bibliography in Computer and Thought, Feigenbaum, E. A., and Feldman, J., eds.

2. See for example Pattee, H. H., "Physical Basis and Origins of Control," p. 102, in Hierarchy Theory, Pattee, H. H., ed., pp. 73-107.

3. An excellent example of such a non-computerized model is offered by Pask's "chemical computer," a physical analogue, the behavior of which provides the basis for a broader interpretation. See Pask, G., "Physical Analogues to the Growth of a Concept" in Mechanization of Thought Processes, A. Utley, ed., HMSO (1959); pp. 877-922. Also in Pask, G., An Approach to Cybernetics.

4. Pask, G., "The Computer-Simulated Development of Populations of Automata," in Mathematical Biosciences, 4, (1969); pp. 101-127.

5. See Ashby, R., "The Self-Reproducing System," in Aspects of the Theory of Artificial Intelligence, C. A. Muses, ed., pp. 9-16.

6. Ibid., p. 15. The basic concept involved, is that a dynamic process can be defined by a set S of states of a system and the mapping f of that set into itself where f is seen as the "dynamic drive" of the system. According to Ashby, "Reproduction is then one of the invariants that holds over the compound of this system and a set of disturbances that act locally."

7. Ashby, R., "Principles of Self-Organizing Systems," in Principles of Self-Organization, Von Foerster, H., and Zope, G. H., eds., pp. 255-278.

8. Wilkins, L., Social Deviance.

9. Burks, A. W., "Computation, Behavior and Structure in Fixed and Growing Automata," in Self-Organizing Systems, Yovits, M.C., and Cameron, S., eds., pp. 282-309.

10. Apter, M., Cybernetics and Development.

11. Barricelli, N. A., "Numerical Testing of Evolution Theories," Part 1, in Acta-Biotheoretica, Vol. XVI - I/II, (1962); pp. 69-98, as well as Part 2 in Acta-Biotheoretica, Vol. XVI-III/IV, (1963); pp. 100-126.

See also Reed, J., Toombs, R., and Barricelli, N. A., "Simulation of Biological Evolution and Machine Learning" in _J. Theoret. Biol._, 17, (1967); pp. 319-342.

12. Fogel, L. J., Owens, A. J., and Walsh, M. J., "Artificial Intelligence Through a Simulation of Evolution," in _Biophysics and Cybernetic Systems_, Maxfield, Callahan, and Fogel, eds., pp. 131-149.
See also Fogel, et al., _Artificial Intelligence Through Simulated Evolution_.

13. Glushkov, V. M., _Introduction to Cybernetics_. The relevant discussion can be found in pages 273-278.

14. Pask, G., "The Cybernetics of Evolutionary Processes and of Self-Organizing Systems," Proc. 3rd Congr. Inter. Assoc. Cybernetics, Namur, 1961: Gauthier Villars (1965); pp. 27-74.
Pask, G., "A Proposed Evolutionary Model," in _Principles of Self-Organization_, Von Foerster, H. and Zope, G. H., eds., pp. 229-253.
Pask, G., "The Computer-Simulated Development of Populations of Automata." Also Pask, G., _The Cybernetics of Human Learning and Performance_, Chapter 3.

15. Barricelli, N. A., "Numerical Testing of Evolution Theories," Part 1.

16. Barricelli, N. A., "Numerical Testing of Evolution Theories," Part 2.

17. Fogel, L. J., Owens, A. J., and Walsh, M. J., "Artificial Intelligence Through a Simulation of Evolution."

18. Pask, G., "The Cybernetics of Evolutionary Processes and of Self-Organizing Systems," as well as Pask, G., "A Proposed Evolutionary Model."

19. Bonner, J. T., The Evolution of Development.

20. See Pask, G., An Approach to Cybernetics, for example, p. 100. Much of the original work is due to Turing and Von Neuman. But see Loefgren, L., "An Axiomatic Explanation of Complete Self Reproduction," in Bull. Math. Biophys., 30, (1968); pp. 415-424. Also Loefgren, L., "Recognition of Order and Evolutionary Systems," in Computer and Information Sciences II, Tou, J., ed., pp. 165-175.

21. Pask, G., "Cognitive Systems."

22. Fogel, L. J., Owens, A. J., and Walsh, M. J., "Artificial Intelligence Through a Simulation of Evolution," p. 49.

23. See Barricelli, N. A., "Numerical Testing of Evolution Theories," Part 1. And for a general review also Emerson, A. E., "The Impact of Darwin on Biology" in Acta-Biotheoretica, Vol. XV - IV (1962), pp. 176-216.

24. Beer, S., Decision and Control. See the discussion on pages 361-369.

25. *Ibid.*, p. 365.

26. Barricelli, N. A., "Numerical Testing of Evolution Theories," Part 1.

27. *Ibid.* p. 73.

28. The reference is to the computer simulations discussed in previous sections (reference No. 11) in which Barricelli generated an evolutionary process similar in many respects to biological evolution by using self-reproducing entities that are constructed by symbiotic associations of other, more simple, self-reproducing entities, all represented by elements of a numerical nature.

29. The relevant references suggested by Barricelli include:
Kozo-Polansky, B., *Outline of a Theory of Symbiogenesis*, Selkhozgiz (1924).
Sonneborn, T. M., "Beyond the Gene," *Amer. Scient.* XXXVII, pp. 33-59 (1949).
Barricelli, N. A., "Symbiogenetic Evolution Processes Realized by Artificial Methods," *Methodos* IX, 35-36, (1957).

30. See the account given by Emerson in "The Impact of Darwin on Biology."

31. Typical representatives would be:

Dewey, J., "Evolution and Ethics" reprinted (1954) in Sci. Mon. N.Y. LXXVIII, pp. 57-66.

Kropotkin, P., Mutual Aid, A Factor in Evolution, McClure Phillips (1902).

Allee, W. C., "Where Angels Fear to Tread: A Contribution From General Sociology to Human Ethics," Science XCVII, (1943); pp. 514-525.

Huxley, T. H., and Huxley, J. S., Touchstones for Ethics, Harper (1947).

Emerson, A. E., "Dynamic Homeostasis: A Unifying Principle in Organic, Social, and Ethical Evolution," Sci. Mon. LXXVII, pp. 67-85 (1954). --(all quoted by Emerson)

32. Von Foerster, H., "Communication Amongst Automata" in The American Journal of Psychiatry, Vol. 118, No. 10, April (1962); pp. 865-871.

33. Ibid., p. 866.

34. Pask, G., "A Proposed Evolutionary Model."

35. Bonner, J. T., The Evolution of Development. See for example the discussion of developmental processes in the slime mold, where phases of unicellular and aggregate existence are clearly differentiable.

36. Ibid., p. 70.

37. Conrad, M. and Pattee, H. H., "Evolution Experiments With an Artificial Ecosystem" in *J. Theor. Biol.*, 28, (1970); pp. 393-409.

38. Kaufman, S. A., "Metabolic Stability and Epigenesis in Randomly Constructed Genetic Nets" in *J. Theoret. Biol.*, 22, (1969); pp. 437-467.

39. Pask, G., "The Natural History of Networks" in *Self-Organizing Systems*, Yovits, M. C., and Cameron, S., eds., pp. 232-260.
Also Pask, G., "A Proposed Evolutionary Model."

40. Barricelli, N. A., see reference No. 11 above.

41. Pask, G., see reference No. 14 above.

42. Varela, F. G., Maturana, H. R., and Uribe, R., "Autopoiesis: The Organization of Living Systems, Its Characterization, and A Model," *Biosystems*, 5, (1974); pp. 187-196.

43. Pask, G., see reference No. 14 above.

44. Conrad, M. and Pattee, H. H., see reference No. 37 above.

45. *Ibid*.

46. See Pask, G., *An Approach to Cybernetics*, p. 101.

2. SOCIETY AS A BRAIN

1. See Bronowski, J., "New Concepts in the Evolution of Complexity: Stratified Stability and Unbounded Plans," in Zygon, Vol. 5, No. 1 (1970), pp. 18-35.
A summary of these views can also be found in Laszlo, E., "A General Systems View of Evolution and Invariance," General Systems Year Book, Vol. 29 (1974), pp. 37-43.

2. According to Bronowski, the concept of "stratified stability" explains the consistent direction of evolution in time. The overall direction is set by the sequential build-up of stable configurations, each upon the next lower one. Chance plays a dominant role in the process since: "the stable units that compose one layer are the raw material for random encounters which will produce higher configurations, some of which will chance to be stable." Ibid, p. 32.

3. Ibid, p. 31.

4. See Cipolla, C. M., The Economic History of World Population, for a view that emphasizes the role of technology, especially the means of energy production for life support, in the major economic "revolutions" in history.

5. See Eigen, M., "Self-Organization of Matter and the Evolution of Biological Macromolecules," in Die Naturwissenschaften,

58 (1971), pp. 465-523.

6. The emergence of novelty is inherent in the organization, or state, of matter and its surroundings and is not a result of the rise of any new property in principle. See Simpson, G. G., The Meaning of Evolution, for a discussion of the concept of "emergent evolution."

7. To the human observer, these may appear as possessing special properties such as "intelligence," "creativity," "inventiveness" of "life."

8. See Ashby, W. R., Design for a Brain.

9. A typical illustration can be found in the changes of the chemical composition of the atmosphere which followed specific evolutionary steps conditioning the possibilities for further evolution. Thus, for example, the evolution of plants and particularly of photosynthesis, released large quantities of oxygen into the air which had previously consisted almost entirely of nitrogen and carbon dioxide. This oxygen provided a protection from lethal radiation and made it generally possible for living organisms to move out of the oceans and occupy the dry land.
(See Luria, S. E., Life the Unfinished Experiment.

10. The question of whether evolution has a direction, or whether it is an entirely random opportunistic process has

been a subject of a heated debate. See Simpson, G. G., _The Meaning of Evolution_.

The view taken here is that the idea of a definite direction can be inferred (and reinforced by a cybernetic interpretation) not in the sense of following a prescribed plan, but in the sense that the progression of evolutionary steps shows a consistent logic of favoring variability and selecting for "regulators" of increasingly more comprehensive capabilities.

11. The idea that diversity in individual organisms is actively maintained by natural selection is argued by Bryan Clarke, for example, using data obtained from empirical studies of various snail populations. See Clarke, B., "The Cause of Biological Diversity" in _Scientific American_, Vol. 233, No. 2, August, (1975), pp. 50-60.

The point made here, is that selection, more than just maintaining variety in a specific individual, selects for variability itself. This idea is consistent with the cybernetic formulation of the concept of regulation and it explains the progressive increase of complexity which marks the evolutionary process.

In so far as the process of evolution shows a consistent trend characterized by a progressive increase in the variety of adaptive possibilities and hence, of regulation potential, we can talk about the "evolution of evolution" much in the same sense of Bonner's discussion of the "evolution of development.

12. Ashby, W. R., Design for a Brain, p. 233.

13. For a comprehensive account of the significance of increases in potential variety, their relation to major evolutionary developments, and their associated survival advantage, see Bonner, J. T., The Evolution of Development. Most of the examples given in the text below have been cited by Bonner.

14. On this point see in particular Ashby's discussion in Design for a Brain.

15. The tremendous survival advantage gained with the emergence of social systems, culture and civilization has been emphasized by the notion of a clear breaking point in evolution. The point often made is that cultural evolution has developed, "superimposed" on the realizations of biological evolution which had preceded it. For a full account see: Huxley, T. H., and Huxley, J. S., Touchstones for Ethics. As well as Waddington, C. H., "Human Ideals and Human Progress," in World Review, August, (1946), pp. 29-36. Also Dobzhansky, T., Mankind Evolving, Luria, S. E., Life the Unfinished Experiment, and Simpson, G. G., The Meaning of Evolution.

16. The adaptive advantage of language and the shared symbolic representation of objects and relationships is brought about by the provision (among other things) of an efficient method for modelling a complex environment and testing, abstractly, various hypothesis about its dynamics and structure.

Consider this point in relation to Conant, R. C. and Ashby, W. R., "Every Good Regulator of a System must be a Model of that System," in Int. J. of Systems Sciences, Vol. 1, No.2, (1970), pp. 89-97.

17. Evolution is a "multi-dimensional" affair. Its products represent distinct steps in a continuous process but each such step may also evolve in itself. Thus, social systems represent an emergent step in the course of evolution, but as specific systems, societies evolve as well.

18. See Pask, G., "Models for Social Systems and for their Languages," Instructional Science, 1, (4), (1973), pp. 395-445. Also Pask, G. "Some Mechanical Concepts of Goals, Individuals, Consciousness and Symbolic Evolution." Burg Wartenstein Symposium on "The Effects of Conscious Purpose on Human Adaptation," July, (1968).

19. In the context of organizational theory, an "individual" is defined by a class of programs bearing a specific name. See Pask, G., Ref. No. 18 above.

20. See Burks, A. W., "Computation, Behavior and Structure in Fixed and Growing Automata," in Self-Organizing Systems, Yovits, M. C. and Cameron, S., eds., pp. 282-309.

21. This correspondence has various significant philosophical implications bearing upon a view of man and society, the nature

of the relation between the two and the evolution of both.

22. See Holt, A. W., "Information System Theory Project," Technical Report No. RADC-TR-68-305, Rome Air Development Center, (1968).

23. See Petri, C. A., "Communication with Automata," (Trans. by Greene, C. F.), A Supplement to Technical Documentary Report 1, Rome Development Center, (1965).

24. The choice of number of domains and the names given to each is arbitrary in that other options are possible depending on a view point and the specific aspects one wishes to stress. In the context of the present discussion this choice is sufficient for conveying some essential concepts related to the dynamics of stability in society, and particularly for a view of society as a cybernetic system.

25. On the effects of the environment on human activity and on social organization see Huntington, E., Mainsprings of Civilization. For the biological aspects of this interaction see Dobzhansky, T., Mankind Evolving, also Dubos, R., So Human an Animal.

In the discussion which follows the contribution of the biological element is suppressed. It is important nevertheless since, although man is largely a "product" of a culture, his biological make-up imposes definite limits on his actions. See Reynolds, V., The Biology of Human Action.

26. For the place of ethics in human evolution see (in addition to applicable references given earlier) Waddington, C., The Ethical Animal. Also a discussion in Ferkiss, V., Technological Civilization.

27. See Toynbee, A., A Study of History (Abridged edition.)

28. The dynamics of such matching processes involve "self vetoing" mechanisms typical to an ultrastable system. See Ashby, W. R., Design for a Brain, but also Beer, S., Brain of the Firm for a detailed exposition.

29. Examples for mutual constraints include a value system embodied in a dogmatic structure inhibiting scientific development (e.g. Galileo and the church). A rigid traditional social framework inhibiting technological development (India), and many more. Examples for self reinforcing processes, can be found in a technology which makes a refinement in scientific theory possible which in turn affects further technological development; an economy which by creating a surplus frees humans for inventive pursuits which may lead to scientific, organizational and technological improvement and ultimately to more surplus and so on.

30. Such a process operates within domain as well as between them. A typical example is furnished by the evolution of concepts and in particular of scientific theories which is often characterized by a process in which new conceptual integration

follows conditions of "crisis." (A mismatch between components of a theory or between theory and new observational facts.) On this point see Kuhn, T. S., The Structure of Scientific Revolutions.

31. See Bateson, C., Our Own Metaphor, chapters 4 and 5. The original reference is Schwartz, T., "The Paliau Movement in the Admiralty Islands, 1946-54," Anthropological Papers of the American Museum of Natural History, Vol. 49, Pt. 2, (1962).

32. Bateson, G., "Cultural Problems Posed by a Study of the Schizophrenic Process," in Symposium on Schizophrenia, (Auerbach, A., ed.)

33. The term revolution may be quite unfortunate in this context. It is nevertheless commonly applied to the transition from a hunter's to an agrarian economy, the rise of city states and the great technological transformations of the 19th century. See Cipolla, C. M., The Economic History of World Population. Also Childe, G., Man Makes Himself.

34. Childe's description of the rise of civilization in Mesopotamia and Egypt is particularly vivid. See Childe, G., Man Makes Himself. But also Toynbee, A., A Study of History and Toynbee, Mankind and Mother Earth.

35. A typical example can be found in the rise of the early civilizations of Mesopotamia and Egypt. The large scale

agricultural undertakings characterizing both cases, which involved the taming of the lower basins of the Tigris and Euphrates and of the Nile, could be only made possible by expanding the scale of technological operations. These, in turn, demanded an integration of large numbers of people, far exceeding the size of the earlier neolitic communities. To support such a requirement a new social order had to be brought about. It was embodied in a new organizational structure and the development of impersonal economic and political institutions. The alliance of individuals to these was assured by a system of values supportive of an all-mighty centralized authority, and institutionalized in an organized religion and a powerful priesthood.

36. For an excellent illustration dramatizing the rate of change in science and technology, see Fuller, R. B., "Profile of the Industrial Revolution," in W.D.S.D. document no. 3, Southern Illinois University, (1965); pp. 27-33. Also Fuller, R. B., Earth Inc.

37. Szent-Gyorgyi, A., "Snakes Do It. So Must Man." in the New York Times, Sat., March 29, 1975. But see also Szent-Gyorgyi, A., The Crazy Ape.

38. A book by that name illustrates the many trends which characterize this turning point. See Mesarovich, M., and Pestel, E., Mankind at the Turning Point.

39. Beer's "Liberty Machine" and the underlying concepts are especially significant in this respect. See Beer, S., Designing Freedom, as well as Platform for Change.

40. Shakespeare, W., Hamlet, - I.V., pp. 191-192. The original lines read:

> "There are more things in heaven and
> earth, Horatio,
> Than are dreamt of in your philosophy."

APPENDICES

APPENDIX A

EVE-1: SUMMARY OF TECHNICAL DETAILS

APPENDIX A

EVE-1: SUMMARY OF TECHNICAL DETAILS

A-1 About the Hardware and Software

Eve-1 was implemented in FORTRAN on the IBM 360/91 computer of Columbia University. Data input and output was done via CRT terminals in the Department of Biological Sciences of Columbia University, and printouts were made on the computer center's line printer. With an environment consisting of 30 x 30 = 900 nodes, the program requires 100,000 eight-bit bytes of computer memory.

The program operation is controlled via a set of commands which essentially constitute a higher-order language. The program may be run interactively, in which case each command is executed by the program as soon as it is typed in by the operator; or it may be run in an off-line mode, in which case a sequence of commands is typed in prior to the execution of the program. All of the program parameters have internal default definitions in the program, so explicit commands are needed to define only those parameters which are to deviate from the default values in a particular run.

The following sequence of commands defines a specific simulation:

COMMAND	EXPLANATION
INITU	"Initialize universe" given at the beginning of each simulation.
NFOOD 10, 20	Specifies that a maximum of 10 food particles are to be generated each time step in a maximum of 20 tries.
FVAL 10, 40	Specifies that the values of the food particles are to lie in the range between 10 and 40.
CREATE 5, 7 0, 1	Creates an automaton at node 5, 7; the automaton's genotype is 0, 1.
CREATE 13, 28 1, 0	Similarly, creates an automaton of genotype (1, 0) at node 13, 28.
GO 400	Causes the simulation to start and proceed for 400 steps.
FVAL 5, 10	Changes the food value range for food particles (the state of the universe, including food and automata, is unchanged).
GO 200	Continues the simulation, using the new food values, for 200 more steps.
EXIT	Terminates program execution.

Other commands, not shown in the example above, allow for the modification of all other program parameters and for the specification of the type of output desired. With the use of this command language, it is not necessary to modify the program itself in order to produce different specific models or simulations; a single version of the program is used with different sets of such commands for that purpose.

A-2 Model Specification: The Environment

The environment in Eve-1 consists of the nodes of a rectangular grid; the two dimensions of the grid need not be equal. A node is represented by two index numbers (I, J).

Each node may be specified as "inaccessible" in the beginning of a simulation. Inaccessible nodes are not visited by automata and food particles are not produced on them. In practice, therefore, the accessible environment may be any subset of the nodes of the rectangular grid, and may have a great variety of shapes.

Each accessible node may contain at most one food particle and at most one automaton at any given time step.

A food particle is dimensionless and has a "food value" which is assigned to it when it is created. The location (node) and food value of a given food particle do not change during the simulation until the particle is eaten by an automaton. (The generation of food particles is described in Section A-5 of this Appendix.)

A-3 Model Specification: The Automata

An automaton is dimensionless and occupies a single node of the environment in a given time step; it is able to sense ("see") food particles and other automata in its vicinity, and to move to neighboring nodes in subsequent time steps. At most one automaton may occupy one node in a given time step.

There are different species of automata, each characterized by a genotype and a phenotype; all automata of the same species have identical genotypes and phenotypes.

The genotype of a species consists of two "genes": the "sensing gene" (g_s) and the movement gene (g_m). Each gene is an integer number whose value may range from 0 to 4. A genotype is represented by the ordered pair (g_s, g_m). Examples of specific genotypes are (0,3), (1,4), and (2,2). The genotype (0,0) is the "null" genotype and is not allowed to exist. The total number of different genotypes is 5 x 5 - 1 = 24. Each of the 24 possible genotypes may be represented by a letter of the alphabet, as shown in Figure 8, page 108.

The phenotype of a species consists of six numbers determining its behavioral and metabolic characteristics. The "primary characteristics" are: radius of sensing (RS) and radius of movement (RM). The "secondary characteristics" are: metabolic rate (RMETAB), initial food store (FSTORI), food store threshold for reproduction (REPROL), and food store threshold for coalition formation (COMBL). Since the values of these numerical characteristics may be varied, a very large number of behaviorally different species may be defined--at most 24, however, may exist at the same time.

A-4 Internal Data Structure in Eve-1

The program maintains the following data areas:

(a) For each node of the environment (I, J):

- A pointer to the automaton (if any) occupying the node in the current time step: IOCC (I, J, NEW)
- A pointer to the automaton (if any) occupying the node in the previous time step: IOCC (I, J, OLD)
- The value of the food particle (if any) contained by the node: FOOD (I, J)

(b) For each automaton (K):

- The automaton's gene values: GS(K), GM(K)
- The node currently occupied by the automaton: IGR(K, NEW), JGR(K, NEW)
- The node previously occupied by the automaton: IGR(K, OLD), JGR(K, OLD)
- The automaton's food store value: FSTOR(K)
- The automaton's age: AGE(K)

Note: K is actually used as an index not of all existing automata, but of all possible automata for which a "slot" exists in memory; by convention, if IGR(K) = 0, then the Kth automaton does not exist.

(c) For each species characteristic:

- A 5 x 5 species matrix giving the numerical value of the characteristic for each of the 24 species. There are six such matrices. To find the characteristics of the Kth automaton, the program first looks up its gene values, S = GS(K) and M = GM(K). Its six characteristics are then RS(S,M), RM(S,M), FSTORI(S,M), RMETAB(S,M), REPROL(S,M) and COMBL(S,M).

(d) Single parameter values:

- Maximum number of food particles created each time step: NFOOD
- Maximum number of trials in placing a food particle: NFTRY
- Minimum and maximum food values: FVMIN, FVMAX
- Minimum age required of an automaton before it can form a coalition: MCOAGE

(e) Program statistics:

The program maintains various types of statistical information such as population of each species, total number of automata created, etc. These values are used only for output and do not in any way affect the rules of the operation of the model.

A-5 Model Specification: Simulation of One Time Step

As the rules of operation of the model have been discussed at length in Section II of chapter , this section of the Appendix consists primarily of flow charts describing these rules (Figures A.1 through A.5). These flow charts have been abbreviated in order to be made more readable; completely detailed flow charts would have been too elaborate to be comprehensible. (In all flow charts, MAXK stands for the maximum number of possible automata.)

The simulation of a time step proceeds as follows:

(a) The "NEW" arrays are renamed to "OLD" and the previously "OLD" are renamed to "NEW."

(b) The "NEW" arrays are initialized.

(c) New food particles are generated (Figure A.1).

(d) Automata are aged and metabolized (Figure A.2).

(e) Automata sense their environment, move, and feed (Figure A.3).

(f) "Well-fed" automata reproduce (Figure A.4).

(g) "Hungry" automata form coalitions (Figure A.5).

The coalition formation event may be formally described with the use of the functions min and max, defined as follows:

min(a,b) = a or b, whichever is smaller;

max(a,b) = a or b, whichever is greater.

Using these functions, we can say that two automata with genotypes $(g_s{}^1, g_m{}^1)$ and $(g_s{}^2, g_m{}^2)$ form a coalition according to the following rule:

$$(g_s{}^1, g_m{}^1) + (g_s{}^2, g_m{}^2) \rightarrow (\min(g_s{}^1 + g_s{}^2, 4), \min(g_m{}^1 + g_m{}^2, 4))$$
$$+ (\max(g_s{}^1 + g_s{}^2 - 4, 0), \max(g_m{}^1 + g_m{}^2 - 4, 0))$$

where the second automaton produced may be the null automaton (0,0) in which case it is immediately removed from the system.

The following flow chart diagrams describe a simulation of one time step and they should be read in a sequence where an exit of one diagram leads to the entry of the following one.

FIGURE A.1: Generation of food particles in one time step (N counts the food particles, I counts the trials)

FIGURE A.2: Pass 1: Automata are aged and metabolized in one time step. (MAXK is the maximum possible number of automata, i.e. the number of accessible environment nodes).

Figure A.3. Pass 2: Automata see, move and feed in one time step(whenever a target node is occupied or further than the radius of movement, the nearest node to it into which a move is allowed is selected.

Figure A.4 Pass 3: Automata reproduce in one time step.

Figure A.5 Pass 4: Coalition Formations in one time step. (The requirement of minimum age for coalition assures that the same automata do not recombine in the same or consecutive time steps).

A-6 The Program Written in Fortran

```
//          JOB (URXXXXX,4,5000),EVE1,REGION=160K,SC=S BIN=21
/*MAIN SYSTEM=SY1,FAILURE=CANCEL
/*PROCESS MAIN
/*PROCESS CRBEOUT
/*FORMAT RT,DDNAME=SYSMSG
/*FORMAT RT,DDNAME=SYSPRINT
/*FORMAT RT,DDNAME=FT06F001
//JOBLIB DD DSN=WYL.BI.PUB.LOAD,DISP=SHR
//SHOW EXEC PGM=CONSOL,PARM='****************** STARTED'
//IIIIIII EXEC FORTGCLG
//FORT.SYSIN DD *
C ------------------------------------------------------------------
C
C                             EVE1
C
C ------------------------------------------------------------------
      CALL PROG
      RETURN
      END
C
C ------------------------------------------------------------------
C NOTE: THE ARRAYS IGS(K), IGM(K) CORRESPOND TO THE GENE VALUES
C      (AS DESCRIBED IN THE WRITEUP) PLUS ONE (I.E., IGS=GS+1, IGM=GM+1).
C
C        LRS,LRM,IAGE CORRESPOND TO RS,RM,AGE IN THE WRITEUP
C ------------------------------------------------------------------
C
C
      SUBROUTINE PROG
C ::::::::::: COMMONS INITIALIZED IN BLOCK DATA AND INITU :::::::::::
      COMMON/GRID/IOCC(30,30,2),FOOD(30,30),MM,NN,IO,IN
      COMMON/THINGS/IGS(600),IGM(600),IGR(600,2),JGR(600,2),
     *FSTOR(600),IAGE(600),MAXK
      COMMON/ATTR/LRS(5,5),LRM(5,5),RMETAB(5,5),REPROL(5,5),
     *COMBL(5,5),FSTORI(5,5)
      COMMON/PARMV/EPSILN,IBARR,NFTRY,NFOOD,FVMIN,FVMAX,MCOAGE
      COMMON/STAT/NTM,NCR,NCO,NDTH,ITYP(5,5),IPOP(5,5),IPBD,IPC,FMX
C :::::::::::::::::::::::::::::::::::::::
      DATA INITF/0/,NPGRD,NSTAT1/1,1/,NPLOT/0/
      INTEGER COMNUM
      LOGICAL DEBUG,LOG4
C
C  COMMON/CONFIG/ IS REQUIRED BY CHAMAN
C
      COMMON/CONFIG/DUMMY(4),DEBUG,DUMDUM(20)
C :::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
C ::   TO ADD NEW COMMANDS,SET COMNUM TO THE TOTAL NUMBER       ::
C ::   OF COMMANDS, DIMENSION COMND ACCORDINGLY, AND ENTER      ::
C ::   THE COMMAND NAME IN THE DATA STATEMENT FOLLOWING.        ::
C ::   ALSO, MAKE SURE TO MODIFY THE COMPUTED 'GOTO' (STMT 30)  ::
C :::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
      DATA COMNUM/25/
      REAL*8 PARAM(50),COMND(25),STR(20)
      DATA COMND/
     *'        ','*       ','EXIT    ',
     *'NFOOD   ','FVAL    ','CREATE  ','INITU   ','PRSG    ',
     *'PRPARM  ','GO      ','PTIME   ','PBD     ','PCOMB   ',
     *'METROW  ','REPROW  ','COMROW  ','FSTROW  ','BARREN  ',
     *' '/
C :::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
C
C     EXECUTION STARTS HERE
C
      CALL PTIME(TIM)
      DEBUG=.FALSE.
      GO TO 1
```

```
      ENTRY RECOV
1     CONTINUE
10    CONTINUE
C ------------------- READ NEXT COMMAND ---------------------------
C
      CALL RTTY(STR)
      CALL GTPARM(STR,PARAM)
      DO 15 I=1,COMNUM
      IF(COMND(I).EQ.PARAM(1))GO TO 25
15    CONTINUE
      CALL WTTY('*** NO SUCH COMMAND ***',22)
      GO TO 10
C
C
25    CONTINUE
C ::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
C     MODIFY NEXT STATEMENT WHEN ADDING NEW COMMANDS
C ::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
30    GO TO (
     *10,10,100,200,300,400,500,600,650,700 ,800,810,820
     *,900,910,920,930,940
     *),I
C ::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
      CALL WTTY('    *** INAVALID COMMAND ***',27)
      GO TO 10
C
C  ---------------- COMMAND SERVICING ---------------------------
C .   EXIT
C
100   CALL PTIME(TIM)
      STOP
C ---------------------
C
C .   NFOOD NFOOD NFTRY - IF ZEROS, OLD VALUES RETAINED
C
200   N1=INTG4(PARAM(2))
      N2=INTG4(PARAM(3))
      IF(N1.GT.0)NFOOD=N1
      IF(N2.GT.0)NFTRY=N2
      GO TO 10
C ----------------------
C .   FVAL FVMIN FVMAX - SET FOOD VALUE RANGE
C
300   R1=REAL9(PARAM(2))
      IF(R1.GT.EPSILN)FVMIN=R1
      FVMAX=REAL9(PARAM(3))
      IF(FVMAX.LT.FVMIN)FVMAX=FVMIN
      GO TO 10
C
C ----------------------
C
400   I=INTG4(PARAM(2))
      J=INTG4(PARAM(3))
      NA=INTG4(PARAM(4))
      NB=INTG4(PARAM(5))
      IF(MINO(I,J,NA,NB).LT.1)GO TO 10
      IF(I.GT.MM)GO TO 10
      IF(J.GT.NN)GO TO 10
      IF(MAXO(NA,NB).GT.5)GO TO 10
      IF(IOCC(I,J,IN).NE.0)GO TO 10
      CALL CREATE(I,J,NA,NB)
      GO TO 10
C ----------------------
C .   INITU - INITIALIZE UNIVERSE FOR NEW SIMULATION
C
500   CALL INITU
```

```
      INITF=1
      GO TO 10
C ----------------------------
C .   PRSG NSTATI NGRD <NPLOT> <FOODMAX>  - SETS PRINTOUT PARAMETERS
C .        NSTATI=FREQUENCY OF POPULATION PRINTOUT
C .        NGRD  =FREQUENCY OF SNAPSHOT PRINTOUT
C .        NPLOT =FREQUENCY OF PLOT LINE PRINTOUT (IF NONZERO, POPU-
C .                     LATION AND SNAPSHOT PRINTOUTS ARE SUPPRESSED)
C .        FOODMAX=USED TO SCALE FREE FOOD PLOT (ESTIMATE MAX FREE FOOD)
C
600   N1=INTG4(PARAM(2))
      N2=INTG4(PARAM(3))
      N3=INTG4(PARAM(4))
      R1=REAL9(PARAM(5))
      IF(N1.GT.0)NSTAT1=N1
      IF(N2.GT.0)NPGRD=N2
      IF(N3.GE.0)NPLOT=N3
      IF(R1.GT.0.5)FMX=R1
      GO TO 10
C ----------------------------
C .   PRPARM - PRINT MODEL SPECIFICATION PARAMETER VALUES
C
650   CALL WTTY(
     *'-------------------- MODEL PARAMETERS ----------------',55)
      CALL PRPARM
      CALL WTTY(
     *'-----------------------------------------------------',55)
      GO TO 10
C ----------------------------
C .   GO N - SIMULATE N TIME STEPS
C
700   NGO=INTG4(PARAM(2))
      IF(NGO.LT.1.OR.NGO.GT.900)GO TO 10
      IF(INITF.NE.0)GO TO 710
      CALL INITU
      INITF=1
710   CALL STAT1
      CALL PRGRID
      IF(NPLOT.GT.0)CALL IPPLOT
      DO 750 I=1,NGO
      CALL TCYCLE
      IF(NPLOT.GT.0)GO TO 745
      IF(MOD(NTM,NSTAT1).EQ.0)CALL STAT1
      IF(MOD(NTM,NPGRD).EQ.0)CALL PRGRID
      GO TO 750
745   IF(MOD(NTM,NPLOT).EQ.0)CALL PPLOT
750   CONTINUE
C ***TEMP -- CHECK DATA STRUCTURE INTEGRITY
      NUMTH=0
      DO 720 KK=1,MAXK
      IGG=IGR(KK,IN)
      IF(IGG.EQ.0)GO TO 720
      JGG=JGR(KK,IN)
      NUMTH=NUMTH+1
      IF(IOCC(IGG,JGG,IN).EQ.KK)GO TO 720
C
      WRITE(6,715)KK,IGG,JGG,IOCC(IGG,JGG,IN)
715   FORMAT(' BAD THING: K,IG,JG,IOCC=',4I5)
720   CONTINUE
C
      DO 730 II=1,MM
      DO 730 JJ=1,NN
      IOCC1=IOCC(II,JJ,IN)
      IF(IOCC1.LT.1)GO TO 730
      IF(IGR(IOCC1,IN).EQ.II.AND.JGR(IOCC1,IN).EQ.JJ)GO TO 730
      WRITE(6,721)NTM,II,JJ,IOCC1
```

```
721    FORMAT(' BAD NODE: NTM,I,J,IOCC1=',4I5)
730    CONTINUE
C
       IPP=0
       DO 740 II=1,5
       DO 740 JJ=1,5
       IPP=IPP+IPOP(II,JJ)
740    CONTINUE
       IF(IPP.NE.NUMTH)WRITE(6,741)NTM,IPP,NUMTH
741    FORMAT(' BAD COUNTS: NTM,IPOPS,NUMTH=',3I5)
C ***TEMP END
       CALL STAT1
       CALL PRGRID
       GO TO 10
C ------------------------
C .    PTIME - PRINT REMAINING TIME IN THIS RUN
C
800    CALL PTIME(TIM)
       GO TO 10
C ------------------------
C .    PBD T/F  -- PRINT BIRTH, DEATH  EVENTS AS THEY HAPPEN
C
810    IPBD=0
       IF(LOG4(PARAM(2)))IPBD=1
       GO TO 10
C ------------------------
C .    PCOMB T/F  -- PRINT COALITION  EVENTS AS THEY HAPPEN
C
820    IPC=0
       IF(LOG4(PARAM(2)))IPC=1
       GO TO 10
C ------------------------
C .    METROW J V1 V2 V3 V4 V5  - READ JTH ROW OF RMETAB (DOT=NO CHANGE)
C
900    CALL RROW(RMETAB,PARAM)
       GO TO 10
C ------------------------
C .    REPROW J V1 V2 V3 V4 V5  - READ JTH REPROL ROW (DOT=NO CHANGE)
C
910    CALL RROW(REPROL,PARAM)
       GO TO 10
C ------------------------
C .    COMROW J V1 V2 V3 V4 V5  - READ JTH COMBL ROW (DOT=NO CHANGE)
C
920    CALL RROW(COMBL,PARAM)
       GO TO 10
C ------------------------
C .    FSTROW J V1 V2 V3 V4 V5  - READ JTH FSTORI ROW
C
930    CALL RROW(FSTORI,PARAM)
       GO TO 10
C ------------------------
C .    BARREN IBARR - NUMBER OF COLUMNS (ON THE RIGHT) WITH NO FOOD
C
940    N1=INTG4(PARAM(2))
       IF(N1.LT.0.OR.N1.GT.MM)GO TO 945
       IBARR=N1
       GO TO 10
945    CALL WTTY(' **** BAD VALUE ****',20)
       GO TO 10
C
C
       END
C
C
C ***********************************************************
```

```
C
C  MAIN TIME CYCLE SIMULATION ROUTINE
C
C ***************************************************************
      SUBROUTINE TCYCLE
C :::::::::: COMMONS INITIALIZED IN BLOCK DATA AND INITU ::::::::::
      COMMON/GRID/IOCC(30,30,2),FOOD(30,30),MM,NN,IO,IN
      COMMON/THINGS/IGS(600),IGM(600),IGR(600,2),JGR(600,2),
     *FSTOR(600),IAGE(600),MAXK
      COMMON/ATTR/LRS(5,5),LRM(5,5),RMETAB(5,5),REPROL(5,5),
     *COMBL(5,5),FSTORI(5,5)
      COMMON/PARMV/EPSILN,IBARR,NFTRY,NFOOD,FVMIN,FVMAX,MCOAGE
      COMMON/STAT/NTM,NCR,NCO,NDTH,ITYP(5,5),IPOP(5,5),IPBD,IPC,FMX
C ::::::::::::::::::::::::::::::::::::::
      LOGICAL TOPDN
      DATA TOPDN/.FALSE./
      IT=IN
      IN=IO
      IO=IT
      NTM=NTM+1
C       WRITE(6,11)NTM,((ITYP(I,J),IPOP(I,J),I=1,5),J=1,5)
C 11    FORMAT(I4,' >>> ',25(A1,'=',I2))
C ----- GENERATE NEW FOOD - NFOOD PARTICLES OR NFTRY TRIES ------
      NPLACE=0
      DO 230 I=1,NFTRY
      IT=IRANI(MM)
      JT=IRANI(NN)
      IF(IT.GT.MM-IBARR)GO TO 230
      IF(IOCC(IT,JT,IO).LT.0.OR.FOOD(IT,JT).GT.EPSILN)GO TO 230
C
      FOOD(IT,JT)=FVMIN+RAN(FVMAX-FVMIN)
      NPLACE=NPLACE+1
      IF(NPLACE.EQ.NFOOD)GO TO 260
230   CONTINUE
C
C CLEAN UP NEW ARRAYS - PRESERVE INACCESSIBLE NODES, IF ANY
C
260   DO 270 I=1,MM
      DO 270 J=1,NN
      IOCC(I,J,IN)=IOCC(I,J,IO)
      IF(IOCC(I,J,IN).GT.0)IOCC(I,J,IN)=0
270   CONTINUE
C
      DO 280 K=1,MAXK
      IGR(K,IN)=0
      JGR(K,IN)=0
280   CONTINUE
C
C ---------- PASS 1:  AGE, METABOLIZE THINGS ----------
C
      DO 305 K=1,MAXK
      IG=IGR(K,IO)
      IF(IG.EQ.0)GO TO 305
      JG=JGR(K,IO)
C
      NA=IGS(K)
      NB=IGM(K)
      IAGE(K)=IAGE(K)+1
      FSTOR(K)=FSTOR(K)-RMETAB(NA,NB)
      IF(FSTOR(K).GE.0)GO TO 305
C THING DIES OF HUNGER
      IF(IPBD.NE.0)WRITE(6,304)K,IGR(K,IO),JGR(K,IO),ITYP(IGS(K),
     *IGM(K))
304   FORMAT(' HUNGER DEATH: K=',I3,'  NODE=',I2,',',I2,'  TYPE=',A1)
      CALL KILL(K,IO)
305   CONTINUE
```

```
C
C ---------- PASS 2:  MOVE, FEED THINGS ----------------------
C
C SCAN TOP/DOWN OR BOTTOM/UP IN ALTERNATE TIME STEPS
      TOPDN=.NOT.TOPDN
C
      DO 390 KK=1,MAXK
      K=KK
      IF(TOPDN)K=MAXK-KK+1
      IG=IGR(K,IO)
      IF(IG.EQ.0)GO TO 390
      JG=JGR(K,IO)
C
      NA=IGS(K)
      NB=IGM(K)
      IRS=LRS(NA,NB)
      IRM=LRM(NA,NB)
      CALL NEARST(IG,JG,IRS,IFF,JFF,ITT,JTT)
      IF(IFF.EQ.0)GO TO 340
C HERE IF FOOD SEEN - GO TO IT
      CALL MOVON(IG,JG,IRM,IFF,JFF,ICODE)
      IF(ICODE.NE.1)GO TO 390
C HERE IF REACHED FOOD - EAT IT
      FSTOR(K)=FSTOR(K)+FOOD(IFF,JFF)
      FOOD(IFF,JFF)=0.
      GO TO 390
C
C HERE IF FOOD NOT SEEN - CHECK IF A NEIGHBOR WAS SEEN
340   IF(ITT.NE.0)GO TO 350
C HERE IF NO NEIGHBOR WAS SEEN - MOVE RANDOMLY TO 1 OF 4 CORNERS
      CALL MOVR(IG,JG,IRM)
      GO TO 390
C HERE IF A NEIGHBOR SEEN - CHECK IF WE ARE HUNGRY
350   IF(FSTOR(K).GT.COMBL(NA,NB))GO TO 360
C HERE IF HUNGRY - GO TOWARD NEIGHBOR SEEKING COALITION
      CALL MOVON(IG,JG,IRM,ITT,JTT,ICODE)
      GO TO 390
C HERE IF NOT HUNGRY - GO TO CORNER OPPOSITE TO NEIGHBOR
360   IDEL=IG-ITT
      JDEL=JG-JTT
      IOPP=IG+ISIGN(IRM,IDEL)
      JOPP=JG+ISIGN(IRM,JDEL)
C
      IF(IOPP.LT.1)IOPP=1
      IF(JOPP.LT.1)JOPP=1
      IF(IOPP.GT.MM)IOPP=MM
      IF(JOPP.GT.NN)JOPP=NN
C
      CALL MOVON(IG,JG,IRM,IOPP,JOPP,ICODE)
C
390   CONTINUE
C
C
C  --------- PASS 3:  REPRODUCE ALL THINGS ------
C
C FROM NOW ON WORK ONLY ON NEW ARRAYS
C
400   DO 490 K=1,MAXK
      IG=IGR(K,IN)
      IF(IG.EQ.0)GO TO 490
      NA=IGS(K)
      NB=IGM(K)
      IF(FSTOR(K).LT.REPROL(NA,NB))GO TO 490
C THIS THING READY TO REPRODUCE - LOOK FOR SPACE NEXT TO IT
      JG=JGR(K,IN)
      NSTART=IRANI(8)
```

```
      NEND=NSTART+7
      DO 405 NE=NSTART,NEND
      CALL GETNBR(NE,INB,JNB)
      INB=IG+INB
      JNB=JG+JNB
      IF(INB.LT.1.OR.INB.GT.MM.OR.JNB.LT.1.OR.JNB.GT.NN)GO TO 405
      IF(IOCC(INB,JNB,IN).EQ.0)GO TO 410
405   CONTINUE
C HERE IF NO FREE SPOTS - TOO CROWDED TO REPRODUCE
      GO TO 490
C HERE FOR THE ACTUAL REPRODUCTION
410   CALL CREATE(INB,JNB,NA,NB)
      IF(IPBD.NE.0)WRITE(6,411)K,ITYP(NA,NB),INB,JNB,FSTOR(K)
411   FORMAT(' --- REPRODUCTION:   K=',I3,'     TYPE=',A1,'     NODE=',
     *I2,',',I2,'    FSTOR=',F4.0)
      FSTOR(K)=FSTOR(K)-FSTORI(NA,NB)
C
490   CONTINUE
C
C
C ---------- PASS 4:  MAKE COALITIONS ----------------
C
500   DO 590 K1=1,MAXK
      IG1=IGR(K1,IN)
      IF(IG1.EQ.0)GO TO 590
      NA1=IGS(K1)
      NB1=IGM(K1)
      IF((FSTOR(K1).GE.COMBL(NA1,NB1)).OR.(IAGE(K1).LE.MCOAGE))GO TO 590
C THIS THING WILLING TO COMBINE - IS THERE A WILLING NEIGHBOR?
      JG1=JGR(K1,IN)
      NSTART=IRANI(8)
      NEND=NSTART+7
C
      DO 530 NE=NSTART,NEND
      CALL GETNBR(NE,INB,JNB)
      IG2=IG1+INB
      JG2=JG1+JNB
      IF(IG2.LT.1.OR.IG2.GT.MM.OR.JG2.LT.1.OR.JG2.GT.NN)GO TO 530
      K2=IOCC(IG2,JG2,IN)
      IF(K2.LT.1)GO TO 530
C HERE IF AN IMMEDIATE NEIGHBOR FOUND - IS IT WILLING?
      NA2=IGS(K2)
      NB2=IGM(K2)
      IF((FSTOR(K2).LE.COMBL(NA2,NB2)).AND.(IAGE(K2).GE.MCOAGE))GOTO 540
530   CONTINUE
C HERE IF NO WILLING NEIGHBORS
      GO TO 590
C HERE IF THE NEIGHBOR IS ALSO WILLING - COMBINE THEM
540   NNA1=NA1+NA2-1
      NNB1=NB1+NB2-1
      NNA2=1
      NNB2=1
      IF(NNA1.LE.5)GO TO 542
      NNA2=NNA1-4
      NNA1=5
542   IF(NNB1.LE.5)GO TO 545
      NNB2=NNB1-4
      NNB1=5
C DISTRIBUTE COMBINED FOOD STORE PROPORTIONALLY
545   TOT1=NNA1+NNB1-2.
      TOT2=NNA2+NNB2-2.
      FSTOT=FSTOR(K1)+FSTOR(K2)
      FSTOR(K1)=FSTOT*TOT1/(TOT1+TOT2)
      FSTOR(K2)=FSTOT-FSTOR(K1)
C INITIALIZE K1 AS A NEW THING
      IGS(K1)=NNA1
```

```
      IGM(K1)=NNB1
      IAGE(K1)=0
      NCO=NCO+1
      IPOP(NA1,NB1)=IPOP(NA1,NB1)-1
      IPOP(NNA1,NNB1)=IPOP(NNA1,NNB1)+1
      IF(IPC.NE.0)WRITE(6,546)IGR(K1,IN),JGR(K1,IN),
     *ITYP(NA1,NB1),ITYP(NA2,NB2),ITYP(NNA1,NNB1)
546   FORMAT(' ***** COALITION AT ',I2,',',I2,' :  ',A1,'+',A1,'-->',A1)
      IF(NNA2.NE.1.OR.NNB2.NE.1)GO TO 550
C HERE IF SECOND THING NULL - REMOVE IT
      CALL KILL(K2,IN)
      GO TO 590
C HERE IF SECOND THING NOT NULL - RE-INITIALIZE IT
550   IGS(K2)=NNA2
      IGM(K2)=NNB2
      IAGE(K2)=0
      IPOP(NA2,NB2)=IPOP(NA2,NB2)-1
      IPOP(NNA2,NNB2)=IPOP(NNA2,NNB2)+1
      IF(IPC.NE.0)WRITE(6,557)ITYP(NNA2,NNB2)
557   FORMAT('+                              +',A1)
C
590   CONTINUE
C
      RETURN
      END
C
C ***********************************************
C
C INITIALIZATION AND I/O SUBROUTINES
C
C ***********************************************
C
C ROUTINE THAT INITIALIZES THE DATA STRUCTURE FOR NEW SIMULATION
C
      SUBROUTINE INITU
C ::::::::: COMMONS INITIALIZED IN BLOCK DATA AND INITU :::::::::
      COMMON/GRID/IOCC(30,30,2),FOOD(30,30),MM,NN,IO,IN
      COMMON/THINGS/IGS(600),IGM(600),IGR(600,2),JGR(600,2),
     *FSTOR(600),IAGE(600),MAXK
      COMMON/ATTR/LRS(5,5),LRM(5,5),RMETAB(5,5),REPROL(5,5),
     *COMBL(5,5),FSTORI(5,5)
      COMMON/PARMV/EPSILN,IBARR,NFTRY,NFOOD,FVMIN,FVMAX,MCOAGE
      COMMON/STAT/NTM,NCR,NCO,NDTH,ITYP(5,5),IPOP(5,5),IPBD,IPC,FMX
C :::::::::::::::::::::::::::::::::
      DO 10 I=1,MM
      DO 10 J=1,NN
      IOCC(I,J,1)=0
      IOCC(I,J,2)=0
      FOOD(I,J)=0.
10    CONTINUE
C
      DO 20 K=1,MAXK
      IGR(K,1)=0
      IGR(K,2)=0
      JGR(K,1)=0
      JGR(K,2)=0
      IGS(K)=0
      IGM(K)=0
      FSTOR(K)=-1.
      IAGE(K)=-1
20    CONTINUE
C
      DO 30 I=1,5
      DO 30 J=1,5
30    IPOP(I,J)=0
C
```

```
      NCR=0
      NCO=0
      NDTH=0
C
      IO=1
      IN=2
      NTM=0
      RETURN
      END
C
C --------------- OUTPUT GRID -----------------------
C  OLD ARRAY IS USED TO SET UP CHARACTER MAP
C
      SUBROUTINE PRGRID
C :::::::::: COMMONS INITIALIZED IN BLOCK DATA AND INITU ::::::::::
      COMMON/GRID/IOCC(30,30,2),FOOD(30,30),MM,NN,IO,IN
      COMMON/THINGS/IGS(600),IGM(600),IGR(600,2),JGR(600,2),
     *FSTOR(600),IAGE(600),MAXK
      COMMON/ATTR/LRS(5,5),LRM(5,5),RMETAB(5,5),REPROL(5,5),
     *COMBL(5,5),FSTORI(5,5)
      COMMON/PARMV/EPSILN,IBARR,NFTRY,NFOOD,FVMIN,FVMAX,MCOAGE
      COMMON/STAT/NTM,NCR,NCO,NDTH,ITYP(5,5),IPOP(5,5),IPBD,IPC,FMX
C :::::::::::::::::::::::::::::::::::::::::::
      DATA IEMPTY,INACC/'.','#'/,IFOOD/'*'/
C
      DO 100 I=1,MM
      DO 100 J=1,NN
      K=IOCC(I,J,IN)
      IF(K)10,20,30
C HERE IF INACCESSIBLE NODE
10    IOCC(I,J,IO)=INACC
      GO TO 100
C HERE IF EMPTY NODE
20    IOCC(I,J,IO)=IEMPTY
      IF(FOOD(I,J).GT.EPSILN)IOCC(I,J,IO)=IFOOD
      GO TO 100
C HERE IF THING ON NODE
30    IOCC(I,J,IO)=ITYP(IGS(K),IGM(K))
100   CONTINUE
C OUTPUT ARRAY
      NNP1=NN+1
      DO 200 JJ=1,NN
      J=NNP1-JJ
      WRITE(6,101)(IOCC(I,J,IO),I=1,MM)
101   FORMAT('     ',100A1)
200   CONTINUE
      RETURN
      END
C
C
C ----------- OUTPUT BASIC STATISTICS ---------------
C
      SUBROUTINE STAT1
C :::::::::: COMMONS INITIALIZED IN BLOCK DATA AND INITU ::::::::::
      COMMON/GRID/IOCC(30,30,2),FOOD(30,30),MM,NN,IO,IN
      COMMON/THINGS/IGS(600),IGM(600),IGR(600,2),JGR(600,2),
     *FSTOR(600),IAGE(600),MAXK
      COMMON/ATTR/LRS(5,5),LRM(5,5),RMETAB(5,5),REPROL(5,5),
     *COMBL(5,5),FSTORI(5,5)
      COMMON/PARMV/EPSILN,IBARR,NFTRY,NFOOD,FVMIN,FVMAX,MCOAGE
      COMMON/STAT/NTM,NCR,NCO,NDTH,ITYP(5,5),IPOP(5,5),IPBD,IPC,FMX
C :::::::::::::::::::::::::::::::::::::::::::
C COUNT THINGS,FOOD
      NUMTH=0
      NUMFD=0
C
```

```
      DO 100 I=1,MM
      DO 100 J=1,NN
      IF(FOOD(I,J).GT.EPSILN)NUMFD=NUMFD+1
      K=IOCC(I,J,IN)
      IF(K.LT.1)GO TO 100
      NUMTH=NUMTH+1
100   CONTINUE
C
C OUTPUT OVERALL NUMBERS
      WRITE(6,201)NTM,NUMTH,NUMFD,NCR,NCO,NDTH
201   FORMAT(1X,
     *' STEP  AUTOM  FOODP  CREATED  COMBINED  DIED',/,1X,
     *  I4, 3X, I5, 3X, I4, 3X, I5, 4X,  I5,  5X, I4,'   %')
C     PRINT POPULATIONS BY TYPE
      CALL IPATT1(IPOP,'SPECIES POPULATIONS',19)
      RETURN
C
      END
C
C -------------- INITIALIZE PLOT, PRINT A PLOT LINE --------------
C
      SUBROUTINE IPPLOT
C :::::::::: COMMONS INITIALIZED IN BLOCK DATA AND INITU ::::::::::
      COMMON/GRID/IOCC(30,30,2),FOOD(30,30),MM,NN,IO,IN
      COMMON/THINGS/ISS(600),ISM(600),IGR(600,2),JGR(600,2),
     *FSTOR(600),IAGE(600),MAXK
      COMMON/ATTR/LRS(5,5),LRM(5,5),RMETAB(5,5),REPROL(5,5),
     *COMBL(5,5),FSTORI(5,5)
      COMMON/PARMV/EPSILN,IBARR,NFTRY,NFOOD,FVMIN,FVMAX,MCOAGE
      COMMON/STAT/NTM,NCR,NCO,NDTH,ITYP(5,5),IPOP(5,5),IPBD,IPC,FMX
C ::::::::::::: ::::::::::::::::::::::::
      DATA IPER/10/
      LOGICAL*1 ISP(81),ISP1(81),ISP2(81),IRATS(31),IRATS1(31)
      LOGICAL*1 IRATS2(31),FCHAR
      LOGICAL LTEM
      REAL*8 NISP1(21),NISP2(21),NIR1(8),NIR2(8)
      EQUIVALENCE (ISP1(1),NISP1(1)),(ISP2(1),NISP2(1)),
     *(IRATS1(1),NIR1(1)),(IRATS2(1),NIR2(1))
      EQUIVALENCE(LTEM,ITEM)
      LOGICAL*1 LTEM1(4)
      EQUIVALENCE(LTEM,LTEM1(1))
      DATA FCHAR/'*'/
      DATA NISP1/'!       ','  !     ','    !   ','      ! ','        ',
     *'!       ','  !     ','    !   ','      ! ','        ','!'/
      DATA NISP2/'!-------','--!-----','----!---','------!-','--------',
     *'!-------','--!-----','----!---','------!-','--------','!'/
      DATA NIR1/'!       ','  !     ','    !   ','      !'/
      DATA NIR2/'!-------','--!-----','----!---','------!'/
C
C
      IPTM=0
      NCR0=0
      NCO0=0
      NDTH0=0
      WRITE(6,11)FMX
11    FORMAT('1','TIME',1X,31X,'SPECIES POPULATIONS',31X,1X,'TIME',
     *1X,2X,' UNCAPTURED FOOD ',/,
     *6X,'0',8X,'10',8X,'20',8X,'30',8X,'40',8X,'50',8X,'60',8X,'70',
     *8X,'80',5X,'0',3X,'  ',8X,'  ',3X,F8.0,/,
     *1X,3X,'0',1X,'-------------------------------------------',
     *'---------------------------------------------',1X,3X,'0',1X,
     *'----------------------------------')
      RETURN
C
C
      ENTRY PPLOT
```

```
      IPTM=IPTM+1
      IF(MOD(IPTM,IPER).EQ.0)GO TO 60
C HERE MOST OF THE TIME
      DO 30 I=1,81
      ISP(I)=ISP1(I)
30    CONTINUE
      DO 40 I=1,31
40    IRATS(I)=IRATS1(I)
      GO TO 100
C HERE FOR GRADATION
60    DO 65 I=1,81
65    ISP(I)=ISP2(I)
      DO 70 I=1,31
70    IRATS(I)=IRATS2(I)
C SPECIES POPULATION DISPLAY
100   DO 200 I=1,5
      DO 200 J=1,5
      IP=MINO(IPOP(I,J),80)
      IF(IP.EQ.0)GO TO 200
      ITEM=ITYP(I,J)
      ISP(IP+1)=LTEM1(1)
200   CONTINUE
C PLOT FREE FOOD VALUE
      FTOT=0.
      DO 220 I=1,MM
      DO 220 J=1,NN
220   FTOT=FTOT+FOOD(I,J)
      IF=30.*FTOT/FMX
 230  IF=MAXO(IF,0)
      IF=MINO(IF,30)
      IRATS(IF+1)=FCHAR
C
250   IF(MOD(IPTM,IPER).NE.0)GO TO 400
      WRITE(6,301)NTM,(ISP(I),I=1,81),NTM,(IRATS(I),I=1,31)
301   FORMAT(1X,I4,1X,81A1,1X,I4,1X,31A1)
      RETURN
400   WRITE(6,401)(ISP(I),I=1,81),(IRATS(I),I=1,31)
401   FORMAT(1X,4X,1X,81A1,1X,4X,1X,31A1)
      RETURN
      END
C
C
C --------------------- PRINT MODEL PARAMETERS -----------------
C
      SUBROUTINE PRPARM
C ::::::::::: COMMONS INITIALIZED IN BLOCK DATA AND INITU :::::::::::
      COMMON/GRID/IOCC(30,30,2),FOOD(30,30),MM,NN,IO,IN
      COMMON/THINGS/IGS(600),IGM(600),IGR(600,2),JGR(600,2),
     *FSTOR(600),IAGE(600),MAXK
      COMMON/ATTR/LRS(5,5),LRM(5,5),RMETAB(5,5),REPROL(5,5),
     *COMBL(5,5),FSTORI(5,5)
      COMMON/PARMV/EPSILN,IBARR,NFTRY,NFOOD,FVMIN,FVMAX,MCOAGE
      COMMON/STAT/NTM,NCR,NCO,NDTH,ITYP(5,5),IPOP(5,5),IP3D,IPC,FMX
C ::::::::::::::::::::::::::::::::::::::::
      CALL IPATT(LRM,'MOVE RADIUS',11)
      CALL IPATT(LRS,'SEE RADIUS',10)
      CALL PATT(FSTORI,'INITIAL FOOD STORE',18)
      CALL PATT(RMETAB,'METABOLISM RATE',15)
      CALL PATT(REPROL,'REPRODUCTION THRESHOLD (MIN)',28)
      CALL PATT(COMBL,'COALITION THRESHOLD (MAX)',25)
      CALL NTTY(
     *'NFOOD NFTRY MCOAGE FVMIN FVMAX      MM NN MAXK',46)
      WRITE(6,101)NFOOD,NFTRY,MCOAGE,FVMIN,FVMAX,MM,NN,MAXK
101   FORMAT(1X,    I4,I6,I6,2F7.0,I7,I3,I5)
      WRITE(6,102)IBARR
102   FORMAT(1X,/,' IBARR=',I2)
```

```
      RETURN
      END
C
C ---------- ROUTINES TO PRINT AN ATTRIBUTE MATRIX
C
      SUBROUTINE PATT(AMAT,MESS,N)
      REAL AMAT(5,5)
      INTEGER MAT(5,5)
      LOGICAL*1 MESS(1)
C ::::::::: COMMONS INITIALIZED IN BLOCK DATA AND INITU :::::::::
      COMMON/GRID/IOCC(30,30,2),FOOD(30,30),MM,NN,IO,IN
      COMMON/THINGS/IGS(600),IGM(600),IGR(600,2),JGR(600,2),
     *FSTOR(600),IAGE(600),MAXK
      COMMON/ATTR/LRS(5,5),LRM(5,5),RMETAB(5,5),REPROL(5,5),
     *COMBL(5,5),FSTORI(5,5)
      COMMON/PARMV/EPSILN,IBARR,NFTRY,NFOOD,FVMIN,FVMAX,MCOAGE
      COMMON/STAT/NTM,NCR,NCO,NDTH,ITYP(5,5),IPOP(5,5),IPBD,IPC,FMX
C ::::::::::::::::::::::::::::::::::::::::
      WRITE(6,9)(MESS(I),I=1,N)
9     FORMAT(1X,' ------------------------------------',100A1)
C
      WRITE(6,11)((ITYP(I,J),AMAT(I,J),I=1,5),J=1,5)
11    FORMAT(1X,/,(5(5X,A1,'=',F4.0)))
      RETURN
C
C
      ENTRY IPATT(MAT,MESS,N)
      WRITE(6,9)(MESS(I),I=1,N)
C
      WRITE(6,12)((ITYP(I,J),MAT(I,J),I=1,5),J=1,5)
12    FORMAT(1X,/,(5(3X,A1,'=',I4)))
      RETURN
C
C
      ENTRY IPATT1(MAT,MESS,N)
      IF(N.EQ.0)GO TO 15
      WRITE(6,9)(MESS(I),I=1,N)
C
15    WRITE(6,17)(J,(MAT(I,J),I=1,5),(ITYP(I,J),I=1,5),J=1,5)
17    FORMAT('       RS=1 RS=2 RS=3 RS=4 RS=5',/,
     *5(' RM=',I1,5I5,12X,5(A1,4X),/))
      RETURN
      END
C ------------- ROUTINE TO READ A ROW OF AN ATTRIBUTE MATRIX ---
C
      SUBROUTINE RROW(AMAT,PARAM)
C ::::::::: COMMONS INITIALIZED IN BLOCK DATA AND INITU :::::::::
      COMMON/GRID/IOCC(30,30,2),FOOD(30,30),MM,NN,IO,IN
      COMMON/THINGS/IGS(600),IGM(600),IGR(600,2),JGR(600,2),
     *FSTOR(600),IAGE(600),MAXK
      COMMON/ATTR/LRS(5,5),LRM(5,5),RMETAB(5,5),REPROL(5,5),
     *COMBL(5,5),FSTORI(5,5)
      COMMON/PARMV/EPSILN,IBARR,NFTRY,NFOOD,FVMIN,FVMAX,MCOAGE
      COMMON/STAT/NTM,NCR,NCO,NDTH,ITYP(5,5),IPOP(5,5),IPBD,IPC,FMX
C ::::::::::::::::::::::::::::::::::::::::
      REAL AMAT(5,5)
      REAL*8 PARAM(1),DOT/'.       '/,TEM
C
      J=INTG4(PARAM(2))
      IF(J.GE.1.AND.J.LE.5)GO TO 5
      CALL WTTY('*** BAD ROW ***',15)
      GO TO 10
5     DO 10 I=1,5
      TEM=PARAM(I+2)
      IF(TEM.NE.DOT)AMAT(I,J)=REAL9(TEM)
10    CONTINUE
```

```
      RETURN
      END
C
C
C ******************************************************************
C
C  TOP LEVEL PROCESSING ROUTINES - BE BORN, SEE, MOVE, DIE
C
C ******************************************************************
C
C  ROUTINE  THAT FINDS CLOSEST THING, FOOD PARTICLE TO A THING.
C     IFOOD, ITHING ARE RETURNED AS ZEROS IF CORRESPONDING ENTITIES
C     ARE NOT SEEN WITHIN LRS OF THING.
C
      SUBROUTINE NEARST(IG,JG,IR,IFOOD,JFOOD,ITHING,JTHING)
C :::::::::: COMMONS INITIALIZED IN BLOCK DATA AND INITU :::::::::::
      COMMON/GRID/IOCC(30,30,2),FOOD(30,30),MM,NN,IO,IN
      COMMON/THINGS/IGS(600),IGM(600),IGR(600,2),JGR(600,2),
     *FSTOR(600),IAGE(600),MAXK
      COMMON/ATTR/LRS(5,5),LRM(5,5),RMETAB(5,5),REPROL(5,5),
     *COMBL(5,5),FSTORI(5,5)
      COMMON/PARMV/EPSILN,IBARR,NFTRY,NFOOD,FVMIN,FVMAX,MCOAGE
      COMMON/STAT/NTM,NCR,NCO,NDTH,ITYP(5,5),IPOP(5,5),IPBD,IPC,FMX
C ::::::::::::::::::::::::::::::::::::::::
      K=IOCC(IG,JG,IO)
      NA=IGS(K)
      NB=IGM(K)
      RMET=RMETAB(NA,NB)
C
      IFOOD=0
      ITHING=0
      IFD=IR+1
      ITD=IFD
      IMIN=MAX0(1,IG-IR)
      IMAX=MIN0(MM,IG+IR)
      JMIN=MAX0(1,JG-IR)
      JMAX=MIN0(NN,JG+IR)
C
      DO 100 I=IMIN,IMAX
      DO 100 J=JMIN,JMAX
      IF(FOOD(I,J).LT.EPSILN)GO TO 20
C  IF PARTICLE SMALLER THAN RMETAB, NOT VISIBLE
      IF(FOOD(I,J).LT.RMET)GO TO 20
C HERE IF FOOD ON THIS NODE
      ID=MAX0(IABS(IG-I),IABS(JG-J))
      IF(ID.GT.IFD)GO TO 20
      IF(ID.LT.IFD)GO TO 10
C HERE IF THIS PARTICLE AT SAME DIST AS A PREVIOUS ONE
C  THIS IS MEANINGFUL ONLY WHEN FOOD IS EVERYWHERE (8 NEAREST CELLS)
      IF(IRANI(3).GT.1)GO TO 20
C HERE TO REMEMBER THIS FOOD PARTICLE
10    IFD=ID
      IFOOD=I
      JFOOD=J
C NOW LOOK FOR THINGS
20    IF(IOCC(I,J,IO).LT.1)GO TO 100
C HERE IF A THING ON THIS NODE - BUT IGNORE IF IT IS US
      IF(IG.EQ.I.AND.JG.EQ.J)GO TO 100
      ID=MAX0(IABS(IG-I),IABS(JG-J))
      IF(ID.GE.ITD)GO TO 100
C HERE IF THIS IS CLOSEST THING SEEN SO FAR - REMEMBER IT
      ITD=ID
      ITHING=I
      JTHING=J
100   CONTINUE
      RETURN
```

```
      END
C
C ------------ MOVE TOWARDS TARGET ------------------
C  MOVES THING TO CLOSEST NODE TO TARGET THAT IS FREE AND
C   WITHIN LRM OF THING (THAT NODE MAY BE TARGET ITSELF).
C   IF ON TARGET, 1 IS RETURNED IN ICODE - ELSE 0.
C   AVAILABILITY OF NODE IS CHECKED IN BOTH OLD, NEW ARRAYS.
C   ASSUMES THE TARGET IS WITHIN BOUNDS OF GRID.
C   UPDATES ONLY NEW ARRAY.
C
      SUBROUTINE MOVON(IG,JG,IR,ITAR,JTAR,ICODE)
C :::::::::: COMMONS INITIALIZED IN BLOCK DATA AND INITU ::::::::::
      COMMON/GRID/IOCC(30,30,2),FOOD(30,30),MM,NN,IO,IN
      COMMON/THINGS/IGS(600),IGM(600),IGR(600,2),JGR(600,2),
     *FSTOR(600),IAGE(600),MAXK
      COMMON/ATTR/LRS(5,5),LRM(5,5),RMETAB(5,5),REPROL(5,5),
     *COMBL(5,5),FSTORI(5,5)
      COMMON/PARMV/EPSILN,IBARR,NFTRY,NFOOD,FVMIN,FVMAX,MCOAGE
      COMMON/STAT/NTM,NCR,NCO,NOTH,ITYP(5,5),IPOP(5,5),IPBD,IPC,FMX
C ::::::::::::::::::::::::::::::::::::::::
      DATA NMVON/0/
      NMVON=NMVON+1
      IF(IG.NE.ITAR.OR.JG.NE.JTAR)GO TO 20
C HERE IF SITTING ON TARGET ALREADY - JUST UPDATE NEW ARRAY
      ICODE=1
      IT=IG
      JT=JG
C      WRITE(6,91)IG,JG
C91    FORMAT(' SITTING ON TARGET: ',2I4)
      GO TO 150
C
20    DELI=ITAR-IG
      DELJ=JTAR-JG
      ADELI=ABS(DELI)
      ADELJ=ABS(DELJ)
      DIST=AMAX1(ADELI,ADELJ)
      IDIST=DIST+0.1
      ICODE=1
      IF(IDIST.LE.IR)GO TO 100
C HERE IF INTERMEDIATE MOVE NEEDED (TARGET TOO FAR)
      ICODE=0
      SFAC=IR/DIST
      DELI=SFAC*DELI
      DELJ=SFAC*DELJ
C MOVE THING BY DELI,DELJ UNLESS THAT PT TAKEN
100   IDEL=DELI+SIGN(0.1,DELI)
      JDEL=DELJ+SIGN(0.1,DELJ)
      IT=IG+IDEL
      JT=JG+JDEL
C TEST FOR NODE AVAILABILITY IN BOTH ARRAYS
      IF(IOCC(IT,JT,IO).NE.0)GO TO 200
      IF(IOCC(IT,JT,IN).NE.0)GO TO 200
C HERE IF DESIRED NODE AVAILABLE - TAKE IT
150   IF(IT.GE.1.AND.JT.GE.1.AND.IT.LE.MM.AND.JT.LE.NN)GO TO 152
      WRITE(6,151)NMVON,IG,JG,IR,ITAR,JTAR,IT,JT
151   FORMAT(' NMVON,IG,JG,IR,ITAR,JTAR,IT,JT=',8I4)
      CALL EVERR('MOVON 1 ')
152   K=IOCC(IG,JG,IO)
      IOCC(IT,JT,IN)=K
      IGR(K,IN)=IT
      JGR(K,IN)=JT
C*C
C*       IF(NTM.GT.42)WRITE(6,171)K,IG,JG,IT,JT,ITYP(IGS(K),IGM(K))
C*171    FORMAT(' MOVON K=',I3,'  FROM ',I2,',',I2,'   TO ',I2,',',I2,
C*      *'   TYPE=',A1)
      RETURN
```

```
C HERE IF DESIRED NODE TAKEN - SEARCH BRUTE-FORCE FOR CLOSEST NODE
200   ICODE=0
      IMIN=MAX0(1,IG-IR)
      JMIN=MAX0(1,JG-IR)
      IMAX=MIN0(MM,IG+IR)
      JMAX=MIN0(NN,JG+IR)
      MINDST=9999
C
      DO 300 I=IMIN,IMAX
      DO 300 J=JMIN,JMAX
      IADEL=IABS(I-ITAR)
      JADEL=IABS(J-JTAR)
      IDIST=MAX0(IADEL,JADEL)
      IF(IDIST.GE.MINDST)GO TO 300
      IF(IOCC(I,J,IO).NE.0)GO TO 300
      IF(IOCC(I,J,IN).NE.0)GO TO 300
C HERE IF THIS IS BEST FREE NODE SEEN SO FAR - REMEMBER IT
      MINDST=IDIST
      IT=I
      JT=J
300   CONTINUE
      IF(MINDST.NE.9999)GO TO 150
C HERE IF NO BETTER NODE SEEN - NO MOVE...
      IT=IG
      JT=JG
      GO TO 150
C
      END
C
C
C ------------------ MOVE RANDOMLY ---------------------
C  ONE OF THE FOUR CORNERS OF THE LRM REGION (CLIPPED, IF
C   NECESSARY, BY THE GRID BOUNDARY) IS SELECTED RANDOMLY, AND
C   THE THING IS MOVED TO IT OR (IF OCCUPIED) TO THE CLOSEST
C   FREE NODE.
C
      SUBROUTINE MOVR(IG,JG,IR)
C :::::::::: COMMONS INITIALIZED IN BLOCK DATA AND INITU ::::::::::
      COMMON/GRID/IOCC(30,30,2),FOOD(30,30),MM,NN,IO,IN
      COMMON/THINGS/IGS(600),IGM(600),IGR(600,2),JGR(600,2),
     *FSTOR(600),IAGE(600),MAXK
      COMMON/ATTR/LRS(5,5),LRM(5,5),RMETAB(5,5),REPROL(5,5),
     *COMBL(5,5),FSTORI(5,5)
      COMMON/PARMV/EPSILN,IBARR,NFTRY,NFOOD,FVMIN,FVMAX,MCOAGE
      COMMON/STAT/NTM,NCR,NCO,NDTH,ITYP(5,5),IPOP(5,5),IPBD,IPC,FMX
C :::::::::::::::::::::::::::::::::::::::::
      CALL RAN4(IT,JT)
      IT=IT*IR+IG
      JT=JT*IR+JG
      IF(IT.LT.1)IT=1
      IF(JT.LT.1)JT=1
      IF(IT.GT.MM)IT=MM
      IF(JT.GT.NN)JT=NN
      CALL MOVON(IG,JG,IR,IT,JT,ICODE)
      RETURN
      END
C
C ---------------------- CREATE A THING -----------------------
C  THIS ROUTINE SHOULD NOT BE CALLED DURING THE 'MOVE,FEED' LOOP
C   OF THE TCYCLE ROUTINE.
C  THIS ROUTINE ASSUMES THAT THE NODE IS FREE.
C
      SUBROUTINE CREATE(IG,JG,NA,NB)
C :::::::::: COMMONS INITIALIZED IN BLOCK DATA AND INITU ::::::::::
      COMMON/GRID/IOCC(30,30,2),FOOD(30,30),MM,NN,IO,IN
      COMMON/THINGS/IGS(600),IGM(600),IGR(600,2),JGR(600,2),
```

```
     *FSTOR(600),IAGE(600),MAXK
      COMMON/ATTR/LRS(5,5),LRM(5,5),RMETAB(5,5),REPROL(5,5),
     *COMBL(5,5),FSTORI(5,5)
      COMMON/PARMV/EPSILN,IBARR,NFTRY,NFOOD,FVMIN,FVMAX,MCOAGE
      COMMON/STAT/NTM,NCR,NCO,NDTH,ITYP(5,5),IPOP(5,5),IPBD,IPC,FMX
C :::::::::::::::::::::::::::::::::::::::::
      IF(IOCC(IG,JG,IN).NE.0)CALL EVERR('CREATE 1')
      IF(NA.LT.1.OR.NB.LT.1.OR.NA.GT.5.OR.NB.GT.5)CALL EVERR('CREATE 2')
C FIND A FREE CORE BLOCK FOR NEW THING
      DO 10 K=1,MAXK
      IF(IGR(K,IN).EQ.0)GO TO 20
10    CONTINUE
      CALL EVERR('NO SPACE')
C HERE WITH NEW K
20    IOCC(IG,JG,IN)=K
      IGR(K,IN)=IG
      JGR(K,IN)=JG
      IGS(K)=NA
      IGM(K)=NB
      FSTOR(K)=FSTORI(NA,NB)
      IAGE(K)=0
      NCR=NCR+1
      IPOP(NA,NB)=IPOP(NA,NB)+1
C*      IF(NTM.GT.42)WRITE(6,31)K,IG,JG
C*31    FORMAT('  CREATING: K=',I3,'   NODE=',I2,',',I2)
      RETURN
      END
C
C ---------------- KILL A THING ----------------------
C
C ION SHOULD BE IO OR IN - THING SHOULD ALREADY EXIST IN THAT ARRAY
C
      SUBROUTINE KILL(K,ION)
C :::::::::: COMMONS INITIALIZED IN BLOCK DATA AND INITU ::::::::::
      COMMON/GRID/IOCC(30,30,2),FOOD(30,30),MM,NN,IO,IN
      COMMON/THINGS/IGS(600),IGM(600),IGR(600,2),JGR(600,2),
     *FSTOR(600),IAGE(600),MAXK
      COMMON/ATTR/LRS(5,5),LRM(5,5),RMETAB(5,5),REPROL(5,5),
     *COMBL(5,5),FSTORI(5,5)
      COMMON/PARMV/EPSILN,IBARR,NFTRY,NFOOD,FVMIN,FVMAX,MCOAGE
      COMMON/STAT/NTM,NCR,NCO,NDTH,ITYP(5,5),IPOP(5,5),IPBD,IPC,FMX
C :::::::::::::::::::::::::::::::::::::::::
      IF(IOCC(IGR(K,ION),JGR(K,ION),ION).NE.K)CALL EVERR('KILL 1  ')
      NA=IGS(K)
      NB=IGM(K)
      IOCC(IGR(K,ION),JGR(K,ION),ION)=0
      IGR(K,ION)=0
      JGR(K,ION)=0
      IGS(K)=0
      IGM(K)=0
      FSTOR(K)=-1.
      IAGE(K)=-1
      NDTH=NDTH+1
      IPOP(NA,NB)=IPOP(NA,NB)-1
      RETURN
      END
C
C ****************************************************
C
C  LOW LEVEL SUBROUTINES, INDEPENDENT OF THE DATA STRUCTURE
C
C ****************************************************
C
C GIVEN N, RETURN NTH IMMEDIATE NEIGHBOR (AS DEFINED BY II,JJ VECTORS)
C
      SUBROUTINE GETNBR(N,I,J)
```

```
      DIMENSION II(8),JJ(8)
      DATA II/ 1, 1,-1,-1, 1,-1, 0, 0/
      DATA JJ/ 1,-1, 1,-1, 0, 0, 1,-1/
      NI=MOD(N,8)+1
10    I=II(NI)
      J=JJ(NI)
      RETURN
C
C ----------------
C RETURN A PAIR RANDOMLY FROM II,JJ VECTORS
C
      ENTRY RAN3(I,J)
      NI=IRANI(8)
      GO TO 10
C
C ----------------
C RETURN A PAIR RANDOMLY FROM FIRST 4 ITEMS OF II,JJ
C
      ENTRY RAN4(I,J)
      NI=IRANI(4)
      GO TO 10
      END
C
C ----- GET A RANDOM REAL BETWEEN 0 AND A ------
C
      FUNCTION RAN(A)
      DATA IFIRST/0/
      IF(IFIRST.NE.0)GO TO 10
      CALL RANDU(65539,IY,Q)
      IFIRST=1
10    IX=IY
      CALL RANDU(IX,IY,Q)
      RAN=Q*A
      RETURN
      END
C
C
C
C --------------- GET A RANDOM INTEGER BETWEEN 1 AND L ----------
C
      INTEGER FUNCTION IRANI(L)
      IRANI=RAN(FLOAT(L))
      IRANI=IRANI+1
      IRANI=MIN0(L,IRANI)
      IRANI=MAX0(1,IRANI)
      RETURN
      END
C
C ------------------- NON-RECOVERABLE ERROR ROUTINE ----------
C
      SUBROUTINE EVERR(MESS)
      LOGICAL*1 MESS(8)
      WRITE(6,1)(MESS(I),I=1,8)
1     FORMAT('  *** ERROR ***   ',8A1)
      STOP
      END
C
C ***********************************************************
C
C DATA INITIALIZATION FOR VARIABLES IN COMMON
C
C ***********************************************************
C
      BLOCK DATA
      COMMON/GRID/IOCC(30,30,2),FOOD(30,30),MM,NN,IO,IN
      COMMON/THINGS/IGS(600),IGM(600),IGR(600,2),JGR(600,2),
```

```
     *FSTOR(600),IAGE(600),MAXK
      COMMON/ATTR/LRS(5,5),LRM(5,5),RMETAB(5,5),REPROL(5,5),
     *COMBL(5,5),FSTORI(5,5)
      COMMON/PARMV/EPSILN,IBARR,NFTRY,NFOOD,FVMIN,FVMAX,MCOAGE
      COMMON/STAT/NTM,NCR,NCO,NDTH,ITYP(5,5),IPOP(5,5),IPBD,IPC,FMX
C :::::::::::::::::::::::::::::::::::::::::::::::::::::: ::::::::::::::::::::::::::
      DATA MM/30/,NN/30/,IO/1/,IN/2/,MAXK/600/
      DATA NFOOD/10/,NFTRY/20/,MCOAGE/5/
      DATA EPSILN/0.001/,IBARR/0/,FVMIN/50./,FVMAX/50./
      DATA IPBD/0/,IPC/0/,FMX/2000./
      INTEGER LRM/
     *1,1,1,1,1,
     *2,2,2,2,2,
     *3,3,3,3,3,
     *4,4,4,4,4,
     *5,5,5,5,5/
      INTEGER LRS/
     *1,2,3,4,5,
     *1,2,3,4,5,
     *1,2,3,4,5,
     *1,2,3,4,5,
     *1,2,3,4,5/
      REAL RMETAB/
     *10.,12.,14.,16.,18.,
     *12.,14.,16.,18.,20.,
     *14.,16.,18.,20.,22.,
     *16.,18.,20.,22.,24.,
     *18.,20.,22.,24.,26./
      REAL REPROL/
     *150.,180.,210.,240.,270.,
     *180.,210.,240.,270.,300.,
     *210.,240.,270.,300.,330.,
     *240.,270.,300.,330.,360.,
     *270.,300.,330.,360.,390./
      REAL COMBL/
     *50.,60.,70.,80.,90.,
     *60.,70.,80.,90.,100.,
     *70.,80.,90.,100.,110.,
     *80.,90.,100.,110.,120.,
     *90.,100.,110.,120.,130./

      REAL FSTORI/
     *100.,120.,140.,160.,180.,
     *120.,140.,160.,180.,200.,
     *140.,160.,180.,200.,220.,
     *160.,180.,200.,122.,240.,
     *180.,200.,220.,240.,260./
C
      DATA ITYP/
     *'?','A','D','I','P',
     *'B','C','F','K','R',
     *'E','G','H','M','T',
     *'J','L','N','O','V',
     *'Q','S','U','W','X'/
      END
C ***************************************************
C PRINT, RETURN REMAINING TIME
C
      SUBROUTINE PTIME(TIME)
100   TIM=IACCTM(IO)*0.000026/60.
      WRITE(6,101)TIM
101   FORMAT(' EVEI.E -- >>>>>>>>> ',F6.3,'  MINS LEFT  <<<<<<<<<<')
      RETURN
      END
C
C *****************************************************
```

APPENDIX B

CYBERNETICS -- AN INTRODUCTORY OVERVIEW

APPENDIX B

CYBERNETICS -- AN INTRODUCTORY OVERVIEW

B-1 General System Theory and Cybernetics

Present conceptual tools used in the discussion of viable systems that range from the physiological and biological to the psychological, social and certain man-made assemblies, owe a tremendous intellectual debt to two related scientific developments, both of which achieved a sufficient level of rigor and conceptual coherence to emerge as acknowledged major disciplines by the late 1940's.

One such development is associated with Ludwig von Bertalanffy and general system theory, and the other with Norbert Wiener and cybernetics.

A common root for both was the generally spread realization that the classical mechanistic approach of science inherited from the 19th century failed to deal in a satisfactory way with complex and at times elusive entities such as life, thought, mind, value, purpose or society. This led to the appreciation of the fact that the reductionist strategy of scientific investigation which studies various phenomena by analyzing their isolated components was inherently inapplicable to the comprehensive treatment of viable systems.

Living organisms, for example, show essential qualities which add up to more than the simple sum of their isolated parts and which depend on the integrity of the organism preserved as a whole. Hence the need, it was felt, for a new emphasis on a "systemic"-"wholistic" approach in the appropriate fields of scientific research. As Ludwig von Bertalanffy expressed it: "In one way or another, we are forced to deal with complexities, with "wholes" or "systems" in all fields of knowledge. This implies a basic reorientation in scientific thinking."(1)

The notion of "systemic wholeness" led to a growing preoccupation with concepts of organization and had an immediate impact on biology, the behavioral sciences and other fields where the reality of an organized complexity was paramount. Biologists in particular had been early to recognize the critical importance of the concept of organization for the understanding of the living organisms as an integrated, complex whole.(2) The idea gained momentum, and was used to replace earlier notions of "vital forces." These, previously, had seemed essential in order to account for overall qualities in the behavior of organisms which were inexplicable by the simple study of their isolated parts.

The emphasis on the significance of the "systemic-wholistic" approach and the recognition of the underlying importance of the concept of organization became central to both general system theory and cybernetics. Bertalanffy, for instance, "advocated an organic conception in biology which emphasizes consideration of the organism as a whole system, and sees the main objective of biological sciences in the discovery of the principle of organization at its various levels."(3) A similar emphasis on organization, and the general relation between the structure of systems and their behavior, later received a rigorous treatment by Wiener,(4) as cybernetics integrated the concepts of organization, information, communication and control into a coherent system of thought.

Bertalanffy expressed the view that the concept of organization could provide a general unifying principle.(5) Organization appeared to be the crux of various supposedly unrelated phenomena and seemed to bridge different levels of reality. In this particular sense, the idea obtained a special significance for general system theory in its broad search for unifying principles which could relate different systems. This search for unifying systems principles became the major preoccupation of the theory, and Bertalanffy set the goals of the new discipline on the "formulation and derivation of those principles which are valid for systems in general."(6)

The basic idea was not of stressing simple analogies or claiming superficially the fundamental "sameness" of diverse phenomena. Rather, it was predicated on the proposition that there are structural similarities and underlying isomorphisms in different aspects of reality, which are reflected in different fields of study, and which, applied on an appropriate level of abstraction, could enrich the available repertoire of scientific models. Such models could be used, in turn, across the conventional boundaries of established scientific disciplines and help gain a better understanding of the general principles which underlie various observable phenomena. The general approach, it was pointed out, could thus provide a possible base, general enough for the unification of science. (7)

While the concept of organization provides a key to the understanding of complexity, the crux of organization is the mechanism which maintains it invariant. And as general system theory was developing in the direction of exploring for general systems' laws, cybernetics, more specifically, was concentrating on the identification and study of those particular mechanisms which maintain dynamic organizations stable.

Cybernetics focused its attention on the organization of a variety of complex systems, man-made and organic in an attempt to gain an insight into the connection between their structure and performance. It emphasized the view that "the structure of the machine or the organism is an index of the performance that may be expected from it," (8) and went on to reveal the dynamics and the specific nature of the relation between the structure of such systems and their behavior.

It had succeeded in doing so by utilizing new concepts of information and communication and associating these with factors that control behavior. Ultimately, it led to the integration of the notion of information and the idea of purpose through the identification and study of feed-back mechanisms. Cybernetics showed that "mechanisms of feed-back nature are the base of teleological or purposeful behavior in man-made machines as well as in living organisms and in social systems."(9) It thus opened the way for the unambiguous discussion of purposeful systems in functional-organizational terms which related the behavior of "teleological" mechanisms, the logic and form of their goal structure and their environment.

Such terms were universal enough to transcend the unique fabric of a specific system under view. Thus, cybernetics provided a particularly powerful paradigm for the early claims of general system theory,(10) but it went on to develop as a new scientific discipline on its own right.

B-2 The Emergence of Cybernetics

The emergence of cybernetics and its consolidation into a coherent discipline followed the gain of new insights into the general applicability of principles fundamental to problems of regulation. In this respect, the working of control mechanisms already known to servo-engineers, as well as mathematically well-defined concepts developed by information theory and used in the context of communication technology, were found relevant to a broad range of phenomena extending beyond the specialized fields within which they were originally conceived. In this context, "The lead was taken by Norbert Wiener who, with Rosenblueth, called attention to the great generality of the concept of feedback . . . and emphasized that this concept provided a useful relationship between biological and the physical sciences."(11)

A typical example for this generality relates to problems encountered with stabilizing servo-mechanisms, in which violent oscillations can be induced under certain conditions of delay in the error-correcting feedback loops. Such unstable conditions were shown by Wiener and his colleagues to be similar to a neural pathology known as "purpose tremor," which is associated with injuries to the cerebellum and in which muscular control is effected. In a typical case of this sort, "a patient, in trying to perform some voluntary act, like picking up a pencil, overshoots the mark and goes into an uncontrollable oscillation."(12)

It was the disclosure of such analogies and their persistent appearance in systems of different kinds, that brought to light the existence of fundamental organizational similarities in the structure of control mechanisms. When this realization was combined with a new theoretical apparatus, by which concepts of entropy, order, information organization and control were related, it became possible to approach problems of regulation in a general way.

Thus, a chain, or rather, a network of related ideas was developing, which provided important links between the discussion of man-made control systems such as Watt's governor, the thermostat, and the new generation of complex self-regulating machines on the one hand, and the study of the brain, the working of the nervous system, and various problems related to physiology and biology on the other. Wiener has expressed this point very clearly when he wrote: "It is my thesis that the physical functioning of the living individual and the operation of some of the newer communication machines are precisely parallel in their analogous attempt to control entropy through feedback."(13)

The link, to emphasize again, which provided the common ground in the discussion of such different systems--mechanical, biological or electronic, was in "the idea of communication of information and the setting up of self-stabilizing control action."(14) It is this very same idea which established the conceptual foundation underlying the emergence of cybernetics. It emphasizes two central issues: namely, that there exists an organizational isomorphism on the level of mechanisms of regulation, and that with regard to such mechanisms, and consequently the dynamics of systems in general, informational content and the structure of information flow play an essential role.

B-3 Cybernetics -- Sources and General Background

The historical background against which the early ideas of cybernetics have been developed, though relatively recent, is well documented(15) and only a brief description will be given below. In retrospect, the birth of the new discipline preceded a period of intense activity in science and technology. Theoretical breakthrough, particularly in the physical sciences, as well as revolutionary innovations in applied technology were strongly effecting the character of the first decades of the 20th century. The accelerating rate of their proliferation was significant enough to be referred to by many contemporary writers as explosive.(16) It produced, not unlike other typical periods in the history of science, the kind of environment in which the formation of new theories and the integration of new concepts seem to thrive.(17) The need for such a conceptual integration, with specific regard to problems associated with communication and regulation, was fulfilled by the advent of cybernetics.

This conceptual integration was brought about by separate efforts, in a variety of fields, at first isolated, but which were ultimately joined by a common language. In the center of activities was work done in an answer to the growing complexity of technology and the associated need to replace human operators with more effective automatic control mechanisms. This need became pressing during World

War II, when the speed of the newly introduced jetplanes was approaching the speed of anti-aircraft missiles significantly enough to "render obsolete all classical methods of the direction of fire."(18) New means had to be developed for scanning, range and location finding, and fire control, with anticipatory as well as error-correcting capabilities. Wiener and Bigelow collaborated on solving these problems, which involved "the investigation of the theory of prediction and the construction of apparatus to embody these theories."(19)

Circumstances required sensitive controls, quick to react, yet stable, which could anticipate the most likely future position of moving targets and which could effectively correct deviations in following the complicated patterns of flight. It is in this context that the importance of feedback to guidance became apparent. It was also in this connection that the role of information in controlling behavior was brought to light and it became clear that "the problems of control engineering and of communication engineering were inseparable."(20) Both centered essentially around the notion of information by whichever means it was transmitted and in whatever medium it was conveyed.

In specific regard to human performance, similar notions were anticipated by Kenneth Craik(21) who emphasized the regulatory characteristics of mechanisms involved with skill acquisition and memory. His work, incidentally, inspired a group of British scientists, some of whom, notably Ross Ashby, Grey Walter and Albert Uttley, subsequently made important contributions to cybernetics in their own right. But returning to the control engineering problems discussed above, the then newly developed information theory, with its roots in notions central to Gibbs statistical mechanics, became critical to the design problem on which Wiener and Bigelow were working. The final result took the form of a new kind of machine which integrated scanning capabilities with computing functions and sophisticated error-correcting control techniques.

This work signaled a new development in science with a shift of emphasis from power to communication engineering. Problems associated with transmission and accurate reproduction of information rather than those related to energy conversion became central, finding their technological realization in the development of computing machines and systems of servo-control. Reviewing this development in its historical context, Wiener has expressed its significance as follows: "If the seventeenth and early eighteenth centuries are the age of the clocks and the later eighteenth and nineteenth centuries constitute the age of steam engines, the present time is the age of communications and control."(22)

Unlike earlier machines, such as the simple clocks or the typical heat engines, the new automata embodied in adaptive-servo-systems were coupled to their environment by complex circuits of performance of actions and information exchange. In their internal organizations and their mode of interaction with the external world, they showed features previously assumed to exclusively characterize life. They became "elaborate enough to exhibit the troublesome kinds of purposiveness already familiar in biology,"(23) and even the functioning of their basic components resembled those of living organisms, in that "they contained sense organs, effectors, and the equivalent of a nervous system to integrate the transfer of information from one to the other."(24)

By the early 40's the connections between the behavior of these man-made control systems and problems encountered in physiology and neurology were becoming clear, and the theoretic framework for their discussion was being established. It received a clear expression in 1943 when Rosenblueth, Wiener and Bigelow published their classical paper "Behavior Purpose and Teleology." In it they discussed the nature of purposive behavior, tied its essence to organizational principles and to the inner informational structure of systems, removed all notions of vitalism and stated that from a scientific standpoint the "behavioristic analysis of machines and living organisms is largely uniform."(25)

These notions became major topics in a wide ranging discussion, centered around Wiener and his colleagues, in which scientists from various fields became involved. There were control engineers and mathematicians, physiologists, neurophysiologists, information theorists, logicians and early computer scientists.(26) It was soon apparent "that there was a substantial common basis of ideas between the workers in the different fields, [and] that people in each group could already use notions which had been better developed by the others."(27) By 1946, the group expanded to include psychologists, sociologists and anthropologists, as all these various sources were combining to produce what amounted to a new vocabulary and a new system of thought. It was to the credit of Wiener and his close colleagues that they articulated the significance of the newly emerging viewpoint and realized that notions of control and communication were at its core. In 1948 Wiener's _Cybernetics_ was published. The book, which "gave a name to an ongoing way of thinking, and added mathematical stamina to a body of embryonic concepts,"(28) had a powerful impact. The foundations for a new science had been laid.

B-4 Definition of Cybernetics

Chosen as a name for the new discipline, the term cybernetics denotes in itself the central role of feedback mechanisms in control. It is derived from the Greek _kybernetes_, meaning steerman, to which the English _governor_ relates through the Latin _gubernator_.(29) As Wiener pointed out, the word governor had already been applied to a typical feedback mechanism in the case of Watt's steam governor, and in this specific sense it was also used by Clark Maxwell in his mathematical analysis of feedback control which was published in 1868.(30) Hence: "the basic concept which both Maxwell and the investigators of cybernetics mean to describe by the choice of this term is that of a feedback mechanism, which is especially well represented by the steering engine of a ship."(31)

In his original text, Wiener defined cybernetics as "the science of control and communication in the animal and the machine." In another source, he described the field and its goals as follows: "Cybernetics attempts to find the common element in the functioning of automatic machines and of the human nervous system, and to develop a theory which will cover the entire field of control and communication in machines and in living organisms."(32)

While the name, as we have seen, implies the role of feedback mechanisms in the regulation of systems, the definition emphasizes two key notions. Firstly, it classifies control and communication together, indicating the central function of information in processes of control. From this point of view, control is achieved through information exchange in the sense, for example, that "the commands through which we exercise our control over our environment are the kind of information which we impart to it."(33) In other words, systems affect and modify, hence exercise control on one another, through the process of informational interaction.

Secondly, the definition emphasizes the universality of laws of regulation and the fact that, in its essence, the functioning of regulating mechanisms is quite independent of the special-case system which is being controlled. Such a system can be embodied in the flesh or in metal. Thus, from the point of view of regulation, the classical duality of the organic and the inorganic vanishes, and "as subjects of scientific inquiry, humans do not differ from machines."(34)

It is perhaps a healthy attribute of a developing science, that since Wiener's original definition was proposed, quite a few other alternatives have been discussed. These vary in their inherent degree of generality and comprehensiveness as well as in giving emphasis to different aspects of the discipline.

Klir and Valach, for example, have criticized Wiener's definition as being unnecessarily restricting,(35) and have reviewed a broad spectrum of other proposals including one of their own. These range from the very specific:

> "Cybernetics is the science of the quantitative and structural laws governing control systems"(36)

to such definitions as:

> "Cybernetics is the science of control in machines, living organisms and societies and of transmission of signals within them."(37)

and

> "Cybernetics deals with the study of systems of arbitrary character, capable of receiving, storing and processing information and utilizing it for purposes of control and regulation."(38)

or their own definition:

> "Cybernetics is a science dealing, on the one hand, with the study of relatively closed systems from the viewpoint of their interchange of information with their environment, on the other hand with the study of the structures of these systems from the viewpoint of the information interchange between their elements."(39)

And finally to the most general views which regard cybernetics as:

> "The science of the optimization of activity."(40)

or similarly:

> "The art of ensuring the effectiveness of action."(41)

On a closer examination, however, none of these definitions seem to go significantly beyond Wiener's original. Especially if one is willing to view the words "control and communication" in the broad sense of regulation, and the expression "animal and the machine" to signify the universal applicability of the concept to general systems (in the sense of Bertalanffy). In such a case, Wiener's definition would read in effect: "The science of regulation in general systems," or better still, "the science of effective regulation in general systems."

In connection with the problem of definition, Beer has pointed out the important relation between control and organization, in stressing that organization: "is the medium through which control is exercised."(42) Accordingly, he joins some Russian workers in proposing to define cybernetics as "the science of effective organization."(43) This definition does not violate Wiener's original dictum. It has the advantage of being short and comprehensive, and may thus be preferred.

B-5 Scope and Multidisciplinary Characteristics

While its fundamental premises are specific and well defined, the scope of cybernetic inquiry is vast. It is characterized by an approach which articulates the general laws of regulation and goes on to apply them in the context of various specific assemblies. Thus, its investigations into phenomena of considerable diversity gives it a strong multidisciplinary flavor.

The problems it examines are concerned, on one way or another, with organization. "Organization in its widest sense, its evolution within the system, transfer between elements of the system and between the system and its environment."(44) Insofar as it relates the dynamics of organization to informational processes, cybernetics is quite oblivious to considerations of energy metabolism and energy exchange as these may occur within or between systems. It takes such energetic processes for granted and focusses its attention on the informational dynamics of systems. In this respect, its approach differs fundamentally from the approach taken by the natural sciences, where energetic considerations are vital.(45) Thus, cybernetics studies ways of behavior and their relation to manifestations of control in the specific domain of "systems that are open to energy but closed to information and control--systems that are information-tight."(46)

Within this domain, a typical object of cybernetic study is a system--"either constructed, or so abstracted from a physical assembly, that it exhibits interaction between the parts whereby one controls another."(47) In other words, the overall behavior of such a system is interpreted in relation to controlling factors. Its interaction with the world and the dynamic relations between its internal elements are always described in terms of informational processes. The information content and its flow--the transfer of signals between elements--determines the outcome of regulation and in general the total complex of signal paths, the elements they connect and their respective transformation functions, constitute the essence of a cybernetic model.

The power of the cybernetic approach is precisely in the general validity of its models to the discussion of organization and processes of control. In this respect it "offers a single vocabulary and a single set of concepts suitable for representing the most diverse type of systems."(48) For example, if one imagines a system A described by a language a and another system B described by a language b, the essence of the cybernetic approach is in abstracting the principles of regulation and describing these in a language c which is then valid for both systems A and B while remaining independent of the details of their particular characteristics.

The notion of abstracting principles of regulation to a level of comprehensive validity was carried even further by Ashby who had contributed significantly to extending the conceptual vocabulary of cybernetics by insisting on generalizing its methods to all possible behaviors in controllable systems. Ashby took the view that "cybernetics stands to the real machine--electronic, mechanical, neural, or economic--much as geometry stands to a real object in our terrestrial space."(49) In other words, it should provide a general framework "on which all individual machines may be ordered, related and understood."(50) Accordingly, cybernetics should develop by considering "the set of all conceivable systems"(51) to which observable phenomena could then be related. This method, Ashby had emphasized, of working from the abstract and general and only then relating its findings to the particular and empirical--"may help to provide us with what is urgently needed in our studies of such complex systems as the brain and society. Namely, a logic of mechanism."(52)

Complexity is the most outstanding characteristic of systems investigated by cybernetics. It is manifest in the fact that such systems are dynamic, usually large and highly interconnected. As a rule, they defy decomposability into simple isolated elements and are in fact never completely accessible. Observation of their details is inherently incomplete. Developing methods suitable for the study of systems which are intrinsically complex has thus become a central feature of cybernetics and typically "the processes that it studies are to be found among brains, colonies of animals, and economic, social and managerial systems too."(53)

Cybernetics regards each such system essentially as an organization and is chiefly concerned with the means by which it maintains its integrity, stability and viability. In each case such a system is treated as an organic whole, and from the point of view of "effective" survival, its viable behavior is described by the general laws of organization and control. These "constitute the 'management principle' by which systems grow and are stable, learn and adjust, adapt and evolve."(54) With regard to such terms, and specifically from the viewpoint of how they regulate themselves, how they "self-organize," all such systems exhibit typical "brain-like" features and on this level of abstraction cybernetics yields its uniquely powerful insights.

Taking a broad overview, and the risk of oversimplification, it seems possible to identify three major levels in relation to which the development of cybernetics has been taking place. These overlap to a great extent but are sufficiently different to merit distinction.

Firstly, there is the level on which the general theory of cybernetics has been developing. By general theory is meant the logic of mechanisms in the sense of Ashby. The theory articulates the laws of regulation and identifies the embodiment of such laws in control mechanisms upon which the stability of complex organizations depends and by which behavioral patterns conducive to survival are mediated.

In addition to Wiener's early contribution and to Shannon's Theory of Communication,(55) most of Ashby's work on brain-like mechanisms and adaptive behavior (56) belongs to this level. So does McCulloch's work on the logic of neural networks(57) as well as von Foerster(58) and Pask's (59) theory of self-organizing systems. The list is by no means exclusive and is only meant for stressing the underlying common feature of starting from first principles in the search for rigorous and general concepts.

The second level of cybernetics research encompasses work in which aspects of the general theory are brought to bear on experimental situations. The theory of control and the theory of automata, for instance, provide the foundation for experimentation and study of various machines, embodied in actual hardware or simulated. The basic notion is that of the constructability, in principle, of mechanisms which display animal-like behavior. Accordingly, the general interest is in "drawing parallels between organisms and machines and in methods of designing machines which have some of the attributes of organisms."(60)

Existing machines of this kind range from those which display a simple demonstration of purposive behavior to machines which attempt to capture the essence of nervous activities and others which deal with various manifestations of cognition and learning.

Thus, for example, there is Grey Walter's "tortoise,"(61) a goal seeking device designed to steer towards a source of light and capable of going around obstacles placed in its way. There is Ashby's homeostat(62) featuring brain-like "ultrastability." In relation to neurophysiological organization, there is a whole class of finite automata which owe their origin to McCulloch and Pitts. They are associated, for instance, with the work of George(63) and Uttley(64) and include logical nets as well as conditional probability machines exhibiting various aspects of pattern recognition and learning. There are various models of thinking processes and artificial intelligence, associated with Amosov(65), Newell, Shaw and Simon(66) as well as Minsky.(67) And there are adaptive teaching machines, of particular significance Pask's "Eucrates,"(68) which demonstrate the interaction between a "teaching" and a "learning" system. Once again the list is by no means exclusive but points to the common effort attempting to embody in man-made machines manifestations of the higher behavior of animals.

The third and rather broad area includes cases in which aspects of cybernetic theory are applied in the context of other fields. On the one hand there are comprehensive cybernetic theories, especially devised by cyberneticians, to yield a new approach in an otherwise established area. Beer's utilization of cybernetic theory of control in the context of management in industry, business and government,(69) as well as Pask's theory of learning(70) and its embodiment in an adaptive learning-teaching environment, are typical examples.

Similarly, but perhaps on a somewhat more limited scale, there are numerous cases in which various cybernetic notions are incorporated into research done in other fields. Thus, there are economists like Oscar Lang, (71) social anthropologists like Bateson(72) and Rappaport, (73) cognitive psychologists like Miller, Galanter and Pribram; (74) there are biologists, linguists, embryologists and many others who find the interplay with cybernetics useful.

It is especially with respect to this bulk of work that the multidisciplinary character of cybernetics is clearly visible. It is manifest in the recent emergence of new titles which emphasize the overlap of cybernetics with other sciences. These include: biocybernetics, neurocybernetics, psychocybernetics, sociocybernetics, medical cybernetics, engineering cybernetics and so forth. While such distinctions may be useful in describing special branches, they should not, as Beer has warned, be taken as "undermining the transdisciplinary unity of cybernetics itself."(75)

B-6 The Cybernetics of Social Systems -- Early Constraints and Current Approach

The concept of information, which has been central to the development of cybernetics, appeared to be both attractive in the intuitive realization of its wide applicability and limiting, in that its basic notions were developed within the context of a specialized technical field.

As Collin Cherry pointed out, "The concept of communication certainly arises in a number of disciplines; in sociology, linguistics, psychology, economics; in physiology of the nervous system, in the theory of signs, in communication engineering."(76) Commenting specifically on the mathematical theory of communication he added, however, that "attempts to extend it outside the technical field in which it first arose will be fraught with pitfalls."(77) Wiener, too, while acknowledging that "it is certainly true that the social system is an organization like the individual, that it is bound together by a system of communication, and that it has a dynamic in which circular processes of feedback nature play an important part,"(78) warned against similar difficulties.

It seems accurate to say, therefore, that in early years cybernetics developed rather specialized concepts which were immediately useful in dealing with various phenomena observed in physiology and neurology and those which emerged in the context of the new man-made automatic machine complexes. There was a wide-spread feeling that insights provided by cybernetics could be helpful beyond the boundaries of the fields mentioned above, particularly that it could provide new tools for the social sciences. But in the 40's this was regarded only as a hope, and Rosenbleuth, commenting on Wiener's Cybernetics, was rather cautious too, when he wrote that it "suggests a program of inquiry that could extend the use of concepts and techniques of proven value in the physical sciences and technologies to the life sciences and eventually to the study of society."(79)

The difficulty had to do with the situation that the very essence of information theory and the rigour by which it was expressed were not quite suitable for a comprehensive treatment of the social reality. Information theory is basically statistical in character in that the transmission of information is expressed in terms of the probabilities of transmitted alternatives. Communication engineering, Wiener has emphasized, deals typically with a machine which has a multiple and varied input. "To function adequately, it must give a satisfactory performance for the class of inputs which it is statistically expected to receive."(80) While there certainly are many specific issues related to social systems which can be dealt with by statistical notions, the broader and more significant events of the social phenomena cannot be expected to yield sufficiently long statistical runs simply because the conditions underlying social systems continuously change. "Thus, the human sciences are very poor testing-ground for a new mathematical technique: as poor as the statistical mechanics of a gas would be to a being of the order of size of a molecule."(81)

In addition there is the significant fact that the mathematical theory of communication was especially tailored to practical engineering problems. It gave a precise definition to the concept of amount of information and developed analytical tools for specifying the relationships between transmitters, receivers and transmission channels and for commenting on their effective organization with regard to performance. Thus the concept of information "has a slightly limited usage which is characteristic of any term that has been given a precise meaning."(82) The effectiveness of the theory and its rigour were achieved by concentrating on a quantitative analysis of information processes which excludes problems associated with the meaning of messages and how they are interpreted. This in itself would have made the discussion of social systems by strict information theoretic terms, at best trivial.

Subsequent developments, however, have extended the conceptual repertoire of cybernetics beyond the application of such restricting specialized techniques. Indeed, some of the methods referred to earlier made it possible and legitimate to include in the cybernetic discussion questions of meaning and cognition which are crucial to approaching systemic processes typical to social interactions. In this respect, von Foerster has recently introduced an important distinction between "first" and "second order" cybernetics.(83) The distinction refers to the cybernetics of "observed" and "observing" systems respectively, and stresses what amounts to a significant qualitative difference between the two. Thus, von Foerster has observed, "while cybernetics began by developing the epistemology for comprehending and simulating first order regulatory processes in the animal and the machine, cybernetics today provides a conceptual framework with sufficient richness to attack successfully second order processes (e.g., cognition, dialogue, socio-cultural interaction, etc.)."(84)

Typical to the general cybernetic method outlined earlier, the current approach to the cybernetics of society, and social-like processes in the broadest sense, starts by viewing information as constituting the principle upon which maintaining the integrity of systems depends. The basic notion is that "any organism is held together . . . by the possession of means for the acquisition, use, retention and transmission of information."(85) Information channels constitute the structure by which an organization is recognizable as an entity, and the flow of information provides the means by which the system is controlling itself. Furthermore, it is such an information structure which actually defines the boundary of a typical social system in that "properly speaking, the community extends only so far as there extends an effectual transmission of information."(86)

The key to the effective extension of cybernetic methodology, however, is in the development of what Pask has called "the organizational model."(87) The main point is in regarding social-like systems as language-oriented in the sense that the organizational model is: "chiefly concerned with the meaning of statements to the participants and in particular, with the interpretation placed upon statements and how this interpretation occurs."(88) By participants is meant individual systems in interaction or the interacting sub-systems in a complex conceived as a whole. These are regarded as goal-directed basic "building blocks" and the interest is chiefly with the content of information exchange between them and with the rules mediating their interaction.

The approach regards the systems that are selected for study essentially as constituting a media in which computations occur. At the same time, it emphasizes a distinction between the information processes themselves and the media from which they are abstracted. The concern is, thus, with procedures, or programs in the sense of Pask, i.e., formulas for achieving goals, and the critical questions relate to their monitoring, execution, reporduction and evolution as well as to how they are coupled in "conversations."

Typically, a view is taken of social systems "as a system for processing information."(89) This is meant in a non-trivial sense which emphasizes the idea that "biological computing mechanisms, . . . rely upon programs for their survival; they rely, at the individual level, upon programs satisfying vital needs--the basic goals of the organism. They rely, at the social level, upon programs for regulating population density and for achieving societal goals."(90) In this an analogy is made with the working of computing machines and brains in general. Taken on the properly intended level of abstraction, such an analogy yields a useful model and provides the link needed "in order to pass from control techniques to the social issues dealt with in "The Human Use of Human Beings"."(91)

B-7 Summary

In summary, the general impact of cybernetics can be seen in related to the following points:

-- It replaced simple reductionism by an organizational approach to whole systems, the concept of organization being the key to the understanding of complexity.

-- By emphasizing the concept of organization it called attention to the relation between the structure of systems and their behavior.

-- The structure of a system was related to informational processes and their specific form within the system.

-- This form, especially as manifest in feedback mechanisms, was identified with the notion of stability and purpose. The connection between goal-directedness and feedback mechanisms thus made it possible to remove earlier notions of vitalism.

-- Feedback mechanisms were associated with the structure of information flow. Thus, the place of information in setting up self-stabilizing control actions by which systemic processes are mediated was brought to light.

-- The concepts of organization, control and communication were centered around the concept of information. They were developed to cover evolutionary and growth processes as well.

-- In this regard the universality of mechanisms of regulation was emphasized abolishing the duality of the organic and inorganic in relation to processes of control. The principle of organization was shown to transcend the specific fabric of a system under control.

-- The discovery of the central role of information, its content and flow, to the behavioral dynamics of systems and particularly to the notion of regulation has stressed the cybernetic viewpoint of studying systems which are open to energy and closed to information. Information has obtained a similar importance for cybernetics as energy has in the realm of the physical sciences.

-- As a result of extending earlier cybernetic concepts to deal with problems of cognition, socio-cultural interaction and so forth, cybernetics achieved a status of a general science of effective organization. Its broad applicability is manifest by the fruitful interplay with many other disciplines.

To conclude, it seems appropriate to quote Ashby, once more, who emphasized that cybernetics "offers the hope for providing the essential methods by which to attack the ills--psychological, social, economic--which at present are defeating us by their intrinsic complexity."(92) In this may still lie its most important contribution.

NOTES TO APPENDIX B

CYBERNETICS -- AN INTRODUCTORY OVERVIEW

1. Bertalanffy, L., von, General System Theory, p. 5.

2. Ibid., p. 12. Bertalanffy provides a detailed account of these concepts in biology and related fields. In addition to early work of his own (1925-26) he cites Whitehead's philosophy and his Organic Mechanism (1925). Cannon's work on homeostasis (1929 and 1932), etc. See also pp. 89-92 for impact and development of the idea in biology.

3. Ibid., p. 13.

4. Wiener, N., Cybernetics, first published in 1948, the book gave a rigorous expression to these ideas.

5. Bertalanffy, L., von, General System Theory, p. 49. Bertalanffy stressed the point that in contrast with reductionism, a unifying principle could be found in the concept of organization as it appears in all levels of reality.

6. Bertalanffy, L., von., "General System Theory," reprinted in General System Yearbook, Vol. 1 (1956); p. 1.

7. Ibid., p. 8. Bertalanffy emphasized the interdisciplinary nature of General System Theory and its implications for the unification of science. For instance: "a unitary

concept of the world may be based, not upon the possibly futile and certainly far-fetched hope finally to reduce all levels of reality to the level of physics, but rather on the isomorphy of laws in different fields." See also _General System Theory_, p. 48.

8. Wiener, N., _The Human Use of Human Beings_, p. 79.

9. Bertalanffy, L., von, _General System Theory_, p. 44. In this connection, most important is the classic paper by A. Rosenblueth, N. Wiener and J. Bigelow, "Behavior, Purpose and Teleology."

10. Bertalanffy, L., von, _General System Theory_, p. 17, expresses the view that cybernetics is a special branch in a general theory of systems.

11. Cherry, C., _On Human Communication_, p. 57.

12. Wiener, N., _Cybernetics_, p. 8. A similar example is cited in relation to "tabes dorsalis," another nervous disorder, in which case the kinesthetic sense is affected. For a more detailed account, see also "Feedback and Oscillation," Chapter 4 of same reference.

13. Wiener, N., _The Human Use of Human Beings_, p. 38.

14. Cherry, C., _On Human Communication_, p. 58.

15. A detailed and exhaustive account is given by Wiener in the introduction to his book Cybernetics. It also forms a part of the general discussion in both Cybernetics and The Human Use of Human Beings. Other particularly relevant sources include: Ashby, R., An Introduction to Cybernetics, Chapter 1; Pask, G., An Approach to Cybernetics, Chapter 1; Beer, S., Decision and Control, Part III.

See also: George, F. H., Automation, Cybernetics and Society, Chapter 4; Klir and Valach, Cybernetic Modelling, Chapter 3; Cherry, C., On Human Communication, Chapter 2.

16. For the manifestation of the "explosive" development of science in various exponential growth curves, see for example: Fuller, R. B., Profile of the Industrial Revolution. W.D.S.D. Document No. 3 (1965); S.I.U. Also McHale, J., World Facts and Trends.

17. Kuhn, T. S., The Structure of Scientific Revolution.

18. Wiener, N., Cybernetics, p. 5.

19. Ibid., p. 6.

20. Ibid., p. 8. See also McCulloch, W. S., "Recollections of the many sources of Cybernetics," ASC Forum, (Summer 1974); p. 12.

21. See Craik, K., The Nature of Psychology, edited by Sherwood, S.

22. Wiener, N., <u>Cybernetics</u>, p. 39.

23. Pask, G., <u>An Approach to Cybernetics</u>, p. 14.

24. Wiener, N., <u>Cybernetics</u>, p. 43. Such machines, Wiener had emphasized, "lend themselves very well to description in physiological terms."

25. Rosenblueth, A., Wiener, N., and Bigelow, J., "Behavior, Purpose and Teleology" in Phil. of Science, Vol. 10 (1943); p. 22.

26. In addition to Wiener, Rosenblueth and Bigelow, there were physiologists and neurophysiologists, notably Dr. Lorente De No and Warren McCulloch. Mathematicians like Dr. Von-Newman and Walter Pitts. Computer scientists like Dr. Goldstein and others.

27. Wiener, N., <u>Cybernetics</u>, p. 15.

28. Pask, G. "The Cybernetics of Behavior and Cognition Extending the Meaning of 'Goal,'" p. 3. Paper delivered at the International Congress of Cybernetics, London (1969).

29. The English to govern relates to the Latin gubernare--to steer a ship, and through it to the Greek kybernan--to steer. Random House Dictionary.

30. Maxwell, J. C., "On Governors," <u>Proc. Royal Soc. of London</u>, vol. 16 (1868); pp. 270-283. Maxwell defined the

term governor as that "part of a machine by means of which the velocity of the machine is kept nearly uniform, notwithstanding variations in the driving power or the resistance."

31. Wiener, N., "Cybernetics," *Scientific American*, 179 (1948); pp. 14-18.

32. *Ibid.*, p. 14.

33. Wiener, N., *The Human Use of Human Beings*, p. 26.

34. Rosenblueth, A., Wiener, N., Bigelow, J., "Purposeful and non-purposeful behavior," *Phil. of Sci.*, Vol. 17 (1960); p. 326.

35. Klir, J. and Valach, M., *Cybernetic Modelling*, p. 65.

36. Kolman, A., "The Cybernetic paradox and self-knowledge of the brain," *Activitas Nervosa Superior*, Vo. 2 (1960); No. 1, pp. 1-6. Quoted in Klir and Valach, ref. (35), p. 67.

37. Poletaev, I. A., "Signal," Izd. Sov. Radio, Moscow (1958). Quoted in Klir and Valach, ref. (35), p. 67.

38. Kolmogorov, A. N., preface to Russian edition of Ashby's *Introduction to Cybernetics*. Quoted in Klir and Valach, ref. (35), p. 67.

39. Klir, J. and Valach, M., in *Cybernetic Modelling*, p. 69.

40. Novik, I. B. Quoted by Klir and Valach, ref. (35), p. 67.

41. Couffignal, L.; his approach is given by Klir and Valach as well. The definition given above is a free translation from the French as quoted by Pask, An Introduction to Cybernetics, p. 15. The original reference is: Couffignal, L., "Essai d'une definition generale de la cybernetique," in Proc. 2nd Congress, International Association of Cybernetics, Namur (1958).

42. Beer, S., Decision and Control, p. 425.

43. Ibid., p. 425. See also Beer, S., Platform for Change, p. 428.

44. Klir, J., and Valach, M., Cybernetic Modelling, p. 77.

45. The distinction between energy and information and their place in the dynamics of systems is fundamental to cybernetic theory. See for example Ashby, An Introduction to Cybernetics, p. 3, and Ashby, "General System Theory As a New Discipline," in General Systems, Vol. III (1958); p. 283. Also von Foerster, H., "On Self-Organizing Systems and Their Environment" in Self-Organizing Systems, Yovits and Cameron, ed., p. 33.

46. Ashby, R., An Introduction to Cybernetics, p. 4.

47. Pask, G., An Approach to Cybernetics, p. 13.

48. Ashby, R., An Introduction to Cybernetics, p. 4.

49., 50. Ibid., p. 8. For a more detailed discussion see also Ashby, R., "General System Theory As a New Discipline."

51. Ashby, R., "General System Theory As a New Science," p. 2. In surveying general system theory, Ashby suggests this as a strategy particularly suitable for dealing with whole systems of high complexity.

52. Ibid., p. 6. In this respect, Ashby uses crystalography as an example in that it "studies on the one hand those crystals that actually occur in nature; and it also studies, in its mathematical branch, all forms that are conceptually possible.

53. Beer, S., Decision & Control, p. 254. Beer regards cybernetics as "the science of control." Its theory is discharged through management which is "the profession of control."

54. Beer, S., "Managing Modern Complexity," in Cybernetics of Cybernetics, B.C.L. Report No. 73.38 (1974); p. 86.

55. Shannon, C. E., and Weaver, W., The Mathematical Theory of Communication.

56. Ashby, R., Design for a Brain.

57. A beautiful collection of papers can be found in McCulloch's Embodiments of Mind.

58. Von Foerster, H., "On Self-Organizing Systems and Their Environments," in *Self-Organizing Systems*, Yovitz and Cameron, eds., pp. 31-50.

59. See, for example, Pask's "The Natural History of Networks," in *Self-Organizing Systems*, Yovitz and Cameron, eds., pp. 232-263.

60. Young, J. F., *Cybernetics*, p. 49. See also George's discussion in *Automation, Cybernetics and Society*, pp. 45-48.

61. Walter, G., *The Living Brain*, 1953.

62. Ashby, R., *Design for a Brain*.

63. George, F., "Probabilistic Machines," *Automation Progress*, Vol. 3, No. 1 (1958).

"Logical Networks and Behavior," *Bull. Math. Biophys.* 18 (1956); pp. 337-48.

64. Uttley, A. M., "The classification of signals in the nervous system," *EEG Clin. Neurophysiol.*, Vol. 6 (1954); pp. 479-494.

65. Amosov, N. M., "Simulation of Thinking Processes," in *Purposive System*, first annual sympos. of A.S.C. (1968); pp. 35-66.

66. Newell, A., Shaw, J. C., and Simon, H. A., "A variety of intelligent learning in a general problem solver," in

Self-Organizing Systems, Yovits and Cameron, eds., pp. 153-189.

67. Minsky, M., "Steps Towards an Artificial Intelligence," *Proc. I.R.E.*, 49 (1961); pp. 8-30.

68. Pask, G., "Teaching Machine," Proc. 2nd International Conf. on Cybernetics, Namur (1958).

69. Beer, S., *Decision and Control*; also Beer, S., "Towards the Cybernetic Factory," in *Principles of Self-Organization*, von Foerster and Zope, eds., pp. 25-89.

70. In most recent work see, for example, Pask, G., Scott, B. C. E., and Kallikourdis, D., "A theory of conversation and individuals (Exemplified by the Learning Process on CASTE)," *Int. J. Man-Machine Studies* 5 (1973); pp. 443-556.

Also: Pask et al., "The Representation of Knowables," System Research Ltd. (1974).

71. Lang, Oscar, *Introduction to Economic Cybernetics*.

72. Bateson, G., *Steps to an Ecology of Mind*.

73. Rappaport, R., *Pigs for the Ancestors*.

74. Miller, G., Galanter, E., and Pribram, K. H., *Plans and the Structure of Behavior*.

75. Beer, S., in *Cybernetics of Cybernetics*, an entry on p. 3.

76. Cherry, C., <u>On Human Communication</u>, p. 2.

77. <u>Ibid</u>., p. 7.

78. Wiener, N., <u>Cybernetics</u>, p. 24.

79. Rosenblith, W. A., in an "Afterword" to <u>The Human Use of Human Beings</u>, p. 271.

80. Wiener, N., <u>Cybernetics</u>, p. 43.

81. <u>Ibid</u>., p. 25.

82. George, F., <u>Automation, Cybernetics and Society</u>, p. 58.

83. Von Foerster, H., in <u>Cybernetics of Cybernetics</u>.

84. Von Foerster, H., "Cybernetics at Illinois," <u>ASC Forum</u>, Vol. VI, No. 2, (Summer 1974); pp. 21-22.

85. Wiener, N., <u>Cybernetics</u>, p. 161.

86. <u>Ibid</u>., p. 158.

87. See for example Pask, G., "Models for Social Systems and for Their Languages," <u>Instructional Science</u>, 1(4) (1973); pp. 395-445.

88. <u>Ibid</u>., p. 404.

89. The notion was clearly illustrated by Miller, Galanter and Pribram. See <u>Plans and the Structure of Behavior</u>, p. 57.

90. Pask, G., "Models for Social Systems and for Their Languages," p. 443.

91. Pask, G., "Comments on the Cybernetics of Ethical, Sociological and Psychological Systems," in _Progress in Biocybernetics_, Vol. 3 (1966); p. 158.

92. Ashby, R., _An Introduction to Cybernetics_, p. 6.

APPENDIX C

SYSTEMS AND ORGANIZATION

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C-1 The Systems Concept in Science

The term "system" is being used at present so widely and freely that it may be useful to briefly examine its content and define its meaning for the purpose of clarity.

On a superficial level, the term is used to denote any complex--meaning an assembly containing more than two distinguishable interdependent parts--the totality of which is identified by virtue of some "logical" consistency. In this sense, we speak about a system of law, a production system, a specific engineering system, an educational or health delivery system, a communication system, a political system, a system of concepts, a mechanical system, a biological system, and so forth.

The loose daily usage does not place rigorous constraints on the term which serves, in fact, as a symbolic shorthand for emphasizing the notion of a totality. The later is grasped intuitively and is not defined with any precision. The concept has a deeper significance, however, which is rooted in fundamental issues concerning man's view of the world and bears upon the very essence of the scientific method.

In the broadest sense, science, as many writers have emphasized, has always dealt with "systems." It is only recently, however, that the term has obtained a meaning new to the mainstream of the western scientific tradition, and that it became possible to speak about "the emergence of the 'system' as a key concept in scientific research."(1) The main issue was referred to earlier, in the introductory discussion of general system theory and cybernetics. It relates to the dichotomy between reductionism and the need for a wholistic perception of complex phenomena which defy treatment by simple decomposition. It is manifest in the relatively recent orientation in science which has been variously called the "systems view," "systems thinking," or the "systems approach."(2)

As Bertalanffy, who pioneered the approach, has emphasized, "the system problem is essentially the problem of the limitation of analytical procedures in science."(3) Until very recently, the development of western scientific thought was predicated upon the analytical method which since the time of the early Greek philosophers was predominantly atomistic in character. The world was seen essentially as a complex, resolvable into its partial and simpler components. Various entities were investigaged by breaking them down into "handleable" parts with the basic assumption that the understanding of these parts could be then linked by simple causal connections to explain the behavior of the whole. The method was successful enough to provide the foundation for the tremendous development of classical science since Galileo. In fact, so dramatic was this success that its dependence, in the first place, on dealing only with simple aspects of reality could be easily overlooked, and science presented a model which, culminating in Newtonian mechanics, "looked upon the physical universe as an exquisitely designed giant mechanism, obeying elegant deterministic laws of motion."(4)

The successful application of the analytical procedure, Bertalanffy has pointed out, depends on two basic conditions; firstly, parts must be independent to a degree that they can be analyzed separately without having the effect of trivializing the entity which is being investigated. In other words, "interaction between 'parts' [should] be non-existent or weak enough to be neglected."(5) Secondly, it must be possible to simply add up description of partial processes in order to construct a picture of the whole. In a mathematical sense this condition demands that "the relations describing the behavior of parts be linear."(6)

That these conditions are not fulfilled by complex assemblies which are richly connected, that the world is made up, to a great extent, precisely of such complexity and that it is not an additive construct of simple entities has been a major revelation to contemporary science. It lead ultimately to the "synthetic" model of thought associated with the notion of systems. The essential novelty of the approach was emphasized by Beer when he wrote: "As far as I can tell, the Greeks, even that greatest of Greeks, Aristotle, had not the faintest glimmer of understanding here, . . . there is no recognition (that I can find) of the potency of system in western thought until we turn into the nineteenth century--when it came with Hegel. After that the notion all but vanished again."(7)

By the 20th century, however, the classical model was running into difficulties even in the realm of the physical sciences where it had been most successful. It proved particularly limiting in biology, for example, where, by the early 1940's, the traditional analytic procedures were being replaced by an organismic view stressing the notions of "whole" complexities, the interdependence of their parts and the underlying logic of their structures. These notions, together with the emphasis on the idea that the behavior of integrated complex organizations is essentially synergetic, namely that it adds up to more than the sum of the parts and that it is unpredictable by the behavior of any of these parts,(8) became the major features of the systems approach, which "has since played an increasingly larger role in organizing both our lay and scientific view of the world."(9)

The systemic notion of integrative qualities and especially of the importance of relational propositions and the interdependence of elements imply, according to Ackoff,(10) three basic properties which are common to complex systemic organizations. One relates to the fact that in a system, each single element has an effect on the behavior of the whole. The second points out that each element in a system is affected by at least one other element and that none have an independent effect on the whole. The third stresses the idea that, in a system, no subgrouping of elements is possible into totally independent subsystems. Together these three properties account for the essentially synergetic behavior of integrated complexity.

The emergence of the system concept has thus supplemented the classical method with another approach to viewing the world. We are faced here with two basically different models. The one reductionist, emphasizing atomistic aspects of phenomena and tending towards ever-greater specialization, the other wholistic, emphasizing relatedness and the integrative aspects of the world, and tending towards comprehensiveness. The significance of the difference between the two cannot be over-emphasized. It is quite fundamental not only on the technical level of scientific methodology, but maybe more importantly, in the philosophical sense of providing a general guiding concept. It thus reaches to the very core of ethics and bears upon man's concept of his identity and the way he relates to the world. Though different, the two models are not mutually exclusive.(11) Both are useful and can best be developed to complement one another.

In this respect it is worth noting that while systemic notions of wholeness and the interdependence of natural phenomena may be relatively novel to the western scientific tradition, they have been central to various ancient eastern philosophies. While not using explicitly the same systemic terms, such notions have found clear expression in various aspects of Hinduism, Buddhism and Taoism and they are especially well-articulated in the doctrines of Zen and Tao. The point was not lost on writers who, being aware of the limitations of classical science, called for a conceptual integration of east and west.(12) The rise of the system sciences may well provide a basis for such an integration.

C-2 Definition of System

The intuitively obvious approach to defining a system stresses the property of a totality consisting of parts which are dependent on one another. Thus we have definitions of a system as "a complex of elements in mutual interaction,"(13) or similarly, "an entity, conceptual or physical, which consists of interdependent parts."(14) If one wishes to stress the dynamic aspect of systems behavior, it is quite legitimate to substitute "events" for "elements" or "parts" and accordingly a system can be defined as "a set of mutually constrained events."(15) Definitions such as those cited above are generally accepted and their meaning, at least intuitively, is quite clear. It is only when one proceeds with a search for a more rigorous definition of the concept that some difficulties appear. The difficulty in providing a definition which is precise and general at the same time stems, on the one hand, from the fact that with regard to the concept of system, different conceptualizations may appear convenient for different purposes. More significantly, however, it seems that the problem of definition of a system is quite inseparable from problems associated with the nature of knowledge and thus it bears, in one way or another, upon problems of semionics, linguistics and the concept of cognition itself. Different definitions may thus be expected to reflect different attitudes to such problems which to some extent still carry the prints of the age-old dichotomy between mentalism and reality.(16)

With this in mind, it seems that definitions can be related to a few different categories stressing notions that are perceptibly distinct. The first category tends to stress the independent, "objective" existence of a system in the real world. The second emphasizes the part played by cognition, namely by an observer, in defining the coherence we call a system. The third is a formal and rigorous definition which stresses the function of a system as a conceptual construct, regarded essentially as a model--an abstract representation of the real world. Finally, there is the fourth attitude, probably the most comprehensive, which places the definition of that which constitutes the boundaries of "a system" on the process of interaction between an observer and a relevant part of the world. This view stresses the relativity inherent in such an interaction, and the fact that under certain circumstances such an interaction may be significant enough to be regarded as an actual "conversation."

A selection of a few typical examples will serve to illustrate the distinctions. The first category is represented by a definition such as Forrester's who defines a system as "a grouping of parts that operate together for a common purpose."(17) The definition is pragmatic and rather limited. It implies that an observer is typically faced with coherent entities which are defined by the logic of their own purpose. It is this purpose which sets a given system apart from other systems in the real world. For a typical example, Forrester uses an automobile which is defined by its function of "providing transportation." As a concrete system in the real world it has a coherence, seemingly "objective," and independent from the viewpoint of a particular observer. (Unless, of course, he is the designer, for example.) The approach stresses a view of a system as a functional entity identified by a purpose "in it" but it neglects to comment on the role of the observer in defining that purpose.

In contradistinction, the second category stresses the role of a mental act in defining the boundaries of a system. It implies that it is really the observer who decides what will be viewed as a system and that it is he who provides the criteria for such a selection. This is a more general approach which in fact contains the first. A typical example is furnished by Fuller's definition of a system as "the first subdivision of universe into a conceivable entity."(18) It is an observer who is "subdividing" the universe, by isolating the entity he defines as a system from both the macroscopic and microscopic events which are irrelevant for the resolution level of the definition itself. In other words, this act of "subdivision," which can be quite arbitrary, separates the pattern conceived as "the system" from those processes which are external to it, namely its environment, and those which are internal to it and require a finer resolution. Such a subdivision, however, is essentially an act of mental recognition and accordingly, as Beer points out: "A system is not something given in nature but something defined by intelligence."(19)

Whether a system is something that exists as a coherent entity in the real world, or whether its coherence depends on an observer's imposition of a conceptual framework which demarcates it from its otherwise fuzzy background, it is clear that, to a great extent, reality is commonly dealt with through the use of models. These are conceptual constructs or abstract mental representations which depend on a mapping that establishes a correspondence between a specific part of the world and its description. The next class of definitions is strongly related to this particular notion and it implies a view of a system as such a model.

Even if not apparent at first glance, Hall and Fagen's definition belongs here. It states that "a system is a set of objects together with relationships between the objects and between their attributes."(20) Objects are defined as components, physical or conceptual, attributes are properties of such objects and relationships are "those which tie the system together."(21) Other typical representatives are provided by similar but more rigorous definitions which utilize set theoretic terms. Klir and Valach's is a good example.(22) Their definition of a system S, containing elements a_1, a_2, ..., a_n, the environment of which is defined by a_0, depends on the following argument: There is a set $A = \{a_1, a_2, \ldots., a_n\}$ and a set $B = \{a_0, a_1, \ldots., a_n\}$ such that B includes the elements of A and their environment a_0. For every element in B there is a set of input and output quantities. The way by which input quantities of element a_j depend on output quantities of element a_i is denoted by r_{ij} and the set of all $r_{ij}(i,j = 0, 1, \ldots., n)$ is symbolized by R. Accordingly: "every set $S = \{A, R\}$ constitutes a system."(23)

Finally there is the approach, dealt with here as a separate category not because of a fundamental difference but because of its particular usefulness. Set in information theoretic terms, which describe the relations between transmitters and receivers in general, it is especially well-equipped to deal with the relations between observers and systems, in this case regarded as "black boxes." A typical illustration of this approach is offered by Pask who suggests that "the paradigm of a system in Ashby's concept of a black box."(24) The implication is that a system can be defined as "a source of information," and while this is a broad definition indeed, which at first glance may seem much too general, it is in fact quite potent.

The crucial point is that, while a black box may represent anything at all, its contents and boundaries are defined by an informational closure which depends on the observer's choice of a set of relevant attributes. These attributes are the few selected from the many that are possible and their choice may, of course, be quite arbitrary. This arbitrariness, however, can be removed by adoption of the usual scientific procedures of prediction and verification by experiment.

The choice of attributes, which represents the choice of the relevant constraints by which the system is defined, determines the state description of the black box at any given time. Their value is typically conveyed by measuring instruments, organic or especially manufactured for the purpose, the readings of which provide the evidence that constitutes the abstracted representation of chosen properties of the real world. They present the values that variables of the system, or better, variables with which the system is identified, assume at a given time. Hence, incidentally, Ashby's definition of a system as "a list of variables."(25)

By convention, as Pask points out, "the totality of the possible assertions about the variables and their relations to one another is called a universe of discourse."(26) And in this connection, a distinction is made between an observational language used to discuss events which occur within the universe of discourse and another, higher order language used to discuss the system as a whole and its relation to its environment. The general approach thus provides a consistent vocabulary which helps remove many of the logical ambiguities that otherwise beset the definitions and the discussion of systems. This is significant, particularly in cases where there exists a danger of mixing different levels of description.

Before leaving the topic of systems definition, a few words may be appropriate with regard to the problem of the classification of systems. Various attempts at such a classification have been made,(27) but as Klir and Valach note, "no satisfactory classification of systems has been elaborated so far."(28) The difficulty seems to relate to the fact that the relevant material is diverse and rather extensive and that different approaches are applicable, stressing different aims, different viewpoints and different operational criteria.

From the viewpoint of cybernetics, the problem of classification is that of identifying the special class of systems which, of all systems, is relevant and significant for a cybernetic study. We have already discussed the significance of information processes and particularly the notion of informational closure to the cybernetic approach. With these characteristics in mind, Klir and Valach offer a specific definition of a "cybernetic system." It is consistent with their definition of a system in general and defines a cybernetic system by stressing its special characteristics as these relate to informational dynamics and information content. The definition reads as follows:

"A set {A,R} where R is the set of informational or signal relationships r_{ij} $(i,j = 0,1, \ldots, n)$ asserting themselves between the elements of a set $A = \{a_1, a_2, \ldots, a_n\}$ on the one hand and between these elements and the element a_0 (the environment) on the other hand, in a cybernetic system."(29)

A different approach is taken by Beer(30) who offers a classification that is particularly useful in helping put the objects of cybernetic inquiry in focus. Briefly, this classification is developed by adopting two major criteria. The first, relating to the concept of complexity, is a three-fold scheme that describes systems as simple, complex, or exceedingly complex. The other is a two-fold scheme having to do with behavior which is defined as being either deterministic or probabilistic. The outcome of relating these two schemes produces six categories by which various systems are identified. Of particular interest are the last two categories, namely, of systems which are "complex and probabilistic" and those which are "exceedingly complex and probabilistic." Examples given are conditional reflexes and industrial profitability for the former and the economy or the brain for the latter. As Beer points out, "the first of these is, in round terms, the province of operational research; the second is the province of cybernetics."(31)

The interest then is in dynamic systems that register a complex behavior, and with control mechanisms which regulate such behavior. From the cybernetician's point of view, more often than not, such systems will be of exceedingly high complexity, and this complexity will be manifest in a system's high internal variety as well as in the richness of its mode of interaction with the world. On both depends its viability, homeostatic or evolutionary, which is otherwise characterized by irreducibility and by various degrees of self-regulation and self-organization.

C-3 Observation, Behavior and Uncertainty

At the previous section the statement was made that the view of a system as a black box offers a particularly useful paradigm for discussing the problem of observers and the systems with which they interact. Before we proceed to examine this paradigm in relation to the notions of observation, behavior and uncertainty, a brief review of the concept of the black box itself is appropriate.

The concept has originated in the field of electrical engineering, but was shown by Ashby(32) to have a more general validity and a far wider range of application. In its original form associated with electrical systems, the concept was related to the need of deducing the content of a complex piece of equipment by manipulating the input terminals and observing the effect of such a manipulation on the outputs. A need of this kind would arise, for example, when a cause for malfunctioning had to be located but for some reason the equipment itself was to be left intact and could not be dismantled for investigation.

As Ashby has pointed out, this problem is quite general in that "in our daily lives we are confronted at every turn with systems whose internal mechanisms are not fully open to inspection, and which must be treated by the methods appropriate to the black box."(33) The concept thus offers a particularly useful strategy for approaching systems, the structure of which, as a rule, is not accessible to direct investigation, and where conclusions about the functioning of internal mechanisms can only be reached by observing external manifestations of behavior. Typical systems of this kind are encountered in biology, physiology, and psychology and are also related to various economic and social problems. The range is broad, "perhaps as great as science itself."(34)

An observer who is faced with a black box has the facility to manipulate the inputs to the box in various ways, and he can observe the related outputs. The observer and the box are coupled by information channels as shown in Figure C-1, and the outcome of the interaction is summarized in a protocol which "can be regarded as a message that contains information about the box's nature."(35) Facts about the principles underlying the behavior of the black box can then be deduced, by identifying regularities which may govern the observed activity and by giving these an appropriate interpretation.

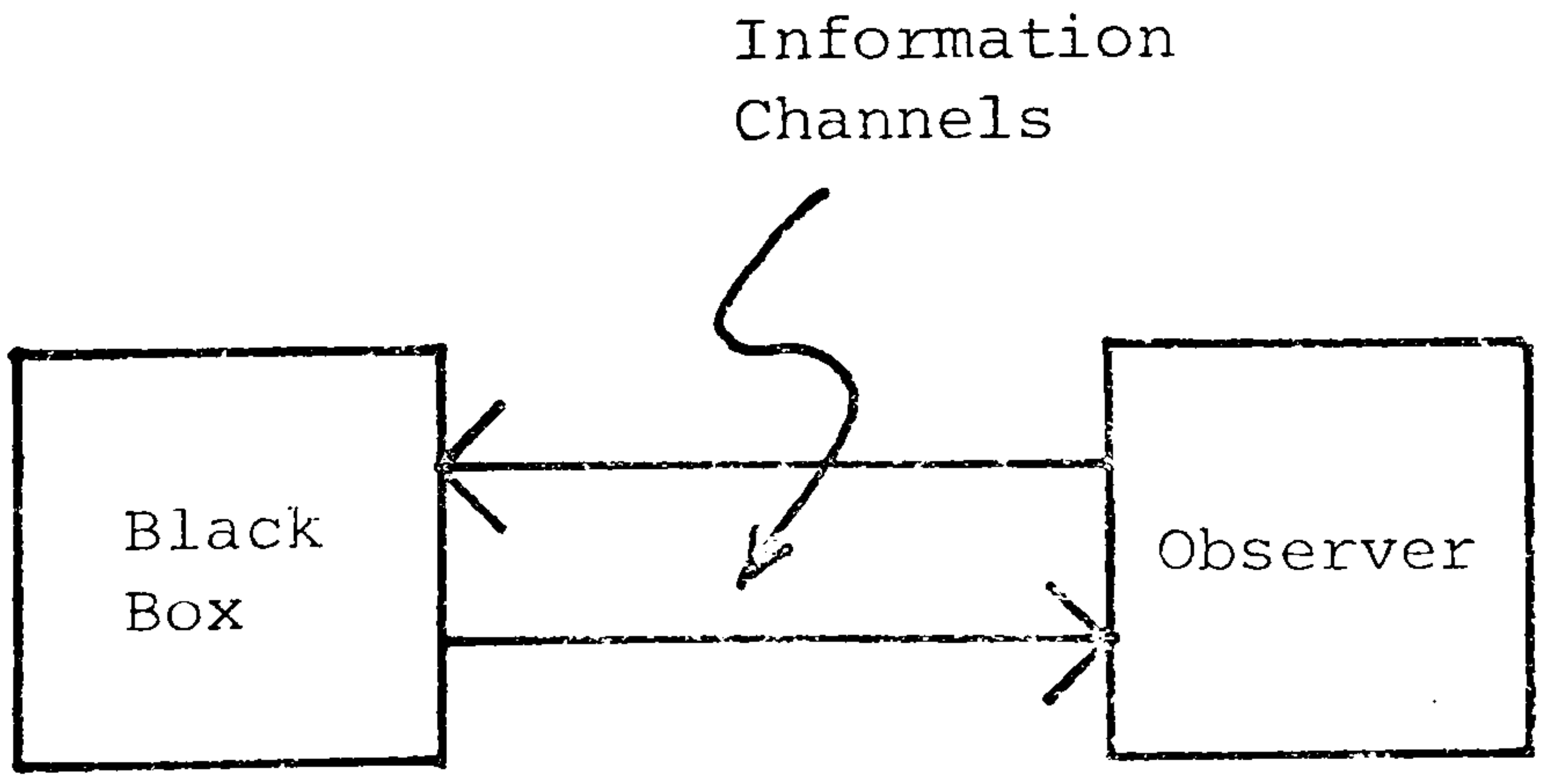

Figure C.1. An Observer and his Black Box

The constraints placed upon the interaction of an observer and a black box are subject to laws of communication which specify the mode of interaction between any two systems where informational closure is assumed. This is the basic reason behind the general validity of the model and the particular usefulness of the terms it employs. These terms will be examined below following, essentially, a discussion offered by Pask.(36)

An observer interacts with a "black box" with a particular purpose in mind. Normally, his purpose would be to reduce his uncertainty about the system, possibly with the intent of eventually being able to make accurate predictions about its behavior. Within the reference frame of our discussion, the concern is specifically with dynamic systems, namely, systems which display activity. The activity itself is a result of an available energy supply which the system consumes as it changes states. From the cybernetic viewpoint, however, energetic considerations are neglected and the interest is wholly with manifestations of behavior and with their description. As the system changes states, it produces a stream of information which is interpreted as evidence about its behavior. This evidence is registered in the observer's measuring devices and is dependent upon the choice of attributes by which his system is identified. Such registered activity, i.e., the behavior itself, "delineates those events that actually do occur . . . from those that are logically possible."(37)

Recalling the black box paradigm of Figure C-1, the observer can be regarded as a typical receiver coupled to a transmitter, or an information source. The sequence of messages received constitutes the behavioral evidence, which in turn is a consequence of changes registered in the outputs of the black box. There are, however, basic limitations placed on the interaction which can be interpreted as fundamental sources of uncertainty. These may be due to limitations inherent in the observer or his measuring instruments, they may be due to an inherent complexity of the black box itself, or they may result from a source of "noise" acting on the information channels. As Pask points out, the model as a whole "is not a picture of things as seen by the observer himself, but a picture as seen by someone looking on from outside at the process of observation."(38)

As he interacts with a black box, the observer obtains the values assumed by inputs and the corresponding values of outputs. For example, he may read X_1 and X_2 for his input and X_3 for his output values. In general, the behavior of the system can be expressed as the transformation T of the inputs X_1 and X_2 into the output X_3, as in Figure C-2 below. Commonly, the expression takes the form of

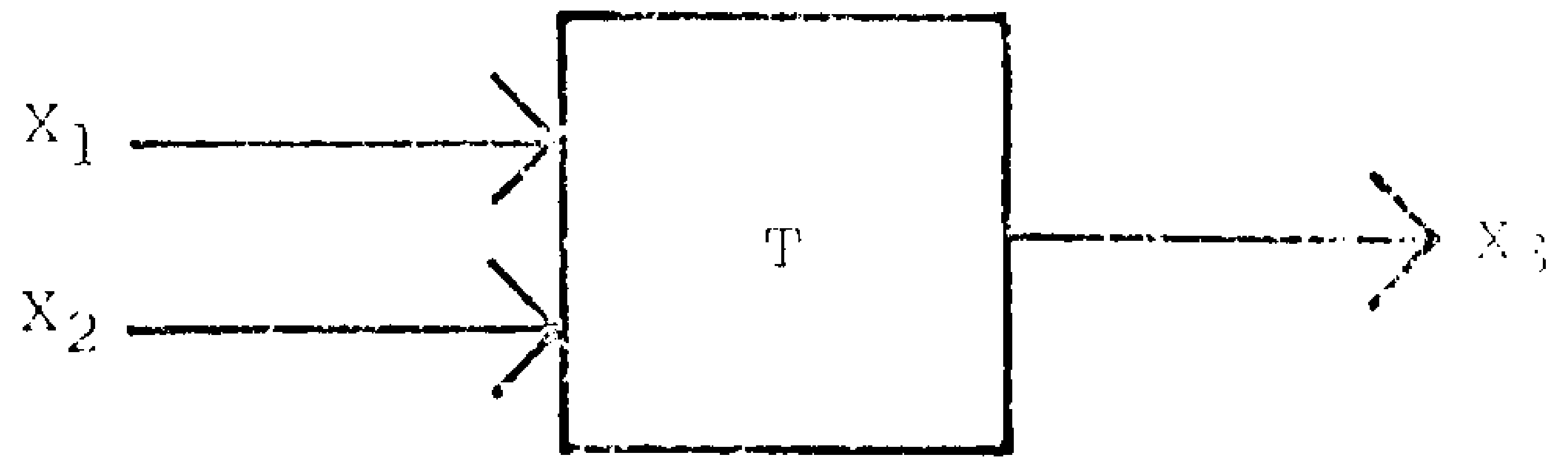

Figure C.2. A Black Box with Inputs X_1, and X_2, an Output X_3 and a transformation Function T.

$X_3 = f(X_1, X_2)$ where f is the transfer function which specifies the transition rule. The observer can manipulate the inputs, thus modifying the parameters of the system, and observe the corresponding changes in output values as he attempts to deduce the transfer function itself.

In general, the values obtained by a sequence of measurements, conveying information about the system's behavior as it changes states with time, can be summarized in various ways, according to need and convenience. By convention, the behavioral protocol can take the form of a simple table of transition states. Otherwise it may be represented by a trajectory in a phase space of n dimensions, where n represents the number of initially unrelated outputs. In yet another typical representation, behavior is described by a state transition graph in which nodes correspond to individual states of the system and the lines connecting them bear the input and output values.

As far as the observer is concerned, dealing with a system entails identifying a universe of discourse U, which can be regarded as an essential constraint that "specifies the logical possibilities an observer can talk about."(39) It also entails a language L by which entities U are identified and their relationships are described. Together, U and L constitute a "reference frame" which is typically chosen by an observer. It is conditioned by his previous experience, by social conventions and so forth. Typically, science makes available a variety of such reference frames which, as Pask points out, are "stereotyped ways of looking at the world."(40) Their usefulness is in providing a common structure through which all individual observations can be coordinated. They facilitate communication, comparison and evaluation of special case experiences, thus contributing to the continuous refinement of specific models and ultimately of science itself.

By setting up the reference frame of U and L, the observer sets the boundaries and the logic by which his interaction with a system is defined. Thus, using L, he may try to predict events in U. In this sense, the "black box" meta-view of observation can describe the hypothetico-deductive method of science whereby observation is followed by the construction of an hypothesis which is then subject to empirical conformation. As he interacts with the system in this fashion, the observer may introduce changes in U, in L or in both. At times, however, he may be compelled to substitute the entire frame of reference U; L for another, a procedure which, as Pask observes, would be associated with a creative act of conceptual innovation.

As an observer learns about a system, he reduces his uncertainty about it but as a general principle uncertainty cannot be entirely removed. There are, for instance, objective limits to the exactness of evidence that can be obtained, in that there are limits to the accuracy achievable in measurements.(41) Notwithstanding cases in which the observer's objectives are unclear to begin with, his interaction with a black box, about which he is trying to learn, is subject to two basic types of uncertainty; metrical and logical.(42) The first relates to uncertainty which is inherent in the values an observer obtains from his measurements, whereas the second is typical to cases where he is uncertain about the structure of the system he is dealing with and about what kind of measurement would be appropriate to begin with.

In principle, some structure in the phenomena observed must be assumed which restricts the logical possibilities of observation. Otherwise there will be no limit to experimentation and no stable conclusion which could be communicated. In order for behavior not to appear chaotic and unintelligible, some regularity must be detected in the protocol. Especially if the observer is to make successful prediction, the system must behave in a "machine"-like fashion. Machine-like in the sense of Ashby, where "knowledge of its present state (as shown at the output) and the conditions within which it is working (that is, the state of its input) is sufficient to determine what it will do next."(43) In other words, the system must be state determined, and in fact, a great deal of the observer's activity will be vested in trying out various procedures, changing U and L, for example, and testing repeatedly for a state determined behavior. If his attempts are unsuccessful, he may choose to try out statistical observations in an effort to establish a statistical determinacy.

We have arrived here at a basic distinction between strictly determinate and statistically determinate behavior. In the first case, the state of the system at time (t+1) depends uniquely on its state at time (t) and upon a fixed transformation function. In other words, when the state of the system at (t) and its transformation function are known, it is always possible to compute its state at (t+1). In the other case (commonly associated with "Markovian" systems), prediction is subject to limitations of probabilistic constraints and the behavior can be described only statistically. Thus, the probability that the system will assume any one of its possible states at time (t+1) depends upon its state at (t) and upon a probabilistic transformation function which is contingent on unvarying transition probabilities. In a general sense, however, it is possible to regard all systems as statistical and maintain that "'Determinate' is the name we give to a system with particularly consistent statistics."(44)

In this context it should be noted that the philosophical meaning underlying the theoretical distinction between deterministic and probabilistic behavior has been in the center of a heated scientific controversy associated particularly with modern physics. The problem reaches beyond questions about predictability of specific events and it bears upon fundamental views concerning the nature of physical phenomena and of order in the universe.(45) We may, however, conclude at this point with Beer, who suggests that from the viewpoint of empirical considerations "we accept as a matter of experimental fact that whereas we are able to describe some systems as if they were deterministic, we are able to describe others only as if they were probabilistic."(46)

C-4 Measuring Complexity -- The Concept of Variety

Systems of high complexity are of particular interest to cybernetics and, as we have seen, high complexity is an essential property of viable systems. Complexity itself does not relate necessarily to the size of systems, when size is taken in the simple sense of adding together elements of a similar kind, in larger and larger quantities. When we add more and more particles to a growing heap of sand, for example, the heap may grow to become very large indeed, but it will remain an essentially simple entity. Complexity, by contrast, is the direct outcome not only of the number of different elements in a system but especially of the fact that these are in a strong and active interaction. It will thus be manifest by the number of different states a system can assume as a result of the dynamic interaction between its elements.

Biological organisms, for example, are commonly referred to as complex systems. Their complexity is due to the fact that the state of the organism at any given time depends on the large number of its physical and chemical processes, all of which interact in an enormously complicated manner. The fact that as a system the organism is also characterized by a significant interaction with the environment only adds a further dimension to the complexity of its internal processes and it is in this sense that "an amoeba is a more complicated system than all systems of the inanimate world."(47) By the time we reach the level of higher organisms or of the human brain with its 10^{10} neurons forming a network that is very rich in interconnections, the complexity is very substantial indeed.

Biological organisms in general, and brains in particular, have become synonymous with the concept of complexity in the sense of being associated with a high degree of interaction of dynamic elements and with the related characteristics of non-reducibility and synergetic behavior. In principle, a similar order of magnitude of complexity, as well as fundamentally similar related properties, are also encountered in the context of many other systems upon which man depends and with which he interacts daily. These range from the ecological to the social and economic contexts in their broadest sense. Complexity, in fact, is a primary qualitative characteristic of most non-trivial situations encountered in the domain of human affairs. It is in this sense that Beer, for example, can talk about business or industry as being viable systems as he emphasizes the significance of complexity in the context of management in general.(48)

Intrinsically high complexity must be accepted, then, as an essential and un-ignorable property of viable systems.(49) In principle it cannot be avoided and therefore techniques for approaching and dealing with complexity are vital. We have already examined in this regard the idea of the black box which offers a method of studying complex systems. An additional and equally important notion has to do with the concept of variety which offers a means for measuring the actual complexity of a system.

Simply defined, the concept of variety refers to the "total number of possible states of a system."(50) In other words, it has to do with the total number of distinguishable states the elements of a given set can assume. The notion of complexity is closely related to the idea of uncertainty, in that the total number of distinguishable states in a typical universe represent, in fact, the uncertainty of an observer facing that universe. The observer is uncertain about which of the many possible states will be actually assumed next. Thus, for a finite well-defined set of elements, the quantity of variety offers a measure of the uncertainty involved as well.

Uncertainty itself relates to the quantity of entropy associated with a given universe, and because the appearance of any one state of possible total n states, removes some uncertainty about the universe by conveying an amount of information, uncertainty and information assume a similar mathematical expression but have opposite signs. Expressed in logarithmic form, their absolute relation is such that:

(Uncertainty) = -(Information)

As Pask notes, "Because of this, observation can either be thought of as removing uncertainty about a set of possibilities, or selection from a set of possibilities can be thought of as a source of information."(51)

The problem of variety and uncertainty has been given a rigorous treatment by von Foerster and his co-workers,(52) who have shown that there exists a formal connection between the two. In general, for any given universe, a specific magnitude of uncertainty corresponds to a particular value of variety. For example, when uncertainty is at maximum, which happens when all events in a universe may occur with equal probability, the variety is naught. Otherwise put, when H and H stand for variety and uncertainty respectively, "if one is ignorant of any regularity in a universe (Variety $H = 0$), one is faced with a universe of maximum uncertainty (H = H max)."(53)

Variety can be expressed in "absolute units of variety" representing directly the number of possible states a given set of elements can assume. For example, in a set of n elements each of which can acquire X different states, the total variety is given by X^n. Thus, in the case of n elements, all with a binary property of being in a certain state or not, the total variety will be 2^n.

As Beer has shown,(54) because of the multiplicative characteristics of the process involved with measuring variety, the values obtained, even for relatively simple cases, tend to be rather large. Typically, such values may be expected to be on the order of magnitude of astronomical figures, a fact which Beer goes on to demonstrate by computing the variety inherent in a relatively simple dyanmic system. According to his example, in such a system, "having only seven components, only one obtrusive relationship between the components, only two modalities of that relationship, and only two conditions of each modality that alternate through time. The variety . . . is 2^{42}, or something greater than 1,000,000,000,000."(55)

In complex systems, variety can thus proliferate very rapidly, but in reality various constraints will be operative in any given situation, limiting the actual number of different states elements in a system can assume, thus reducing variety from its total theoretically possible value. The existence of such constraints which act on the total possible variety is of fundamental significance, in that such constraints underlie the order we perceive in the universe. If elements that constitute the complexity of which the world is composed could assume any arbitrary state at all, prediction would be impossible in principle, and the regularities we call natural laws would have no meaning.

Because of the large numbers usually associated with values of variety and because of the multiplicative characteristics involved with its proliferation, it is a common practice to express variety logarithmically. The binary characteristics of decision in removing uncertainty make it convenient to choose the base two and, accordingly, the variety of a set of n elements takes the form of $\log_2 n$. Measuring variety in binary terms has a particular practical significance as it underlines a strategy which simplifies the problem of removing uncertainty in high variety situations. Thus, for example, using Beer's demonstrated case of the system with variety of 2^{42}, and viewing the problem of removing uncertainty essentially in terms of making binary decisions, the total variety of the process of selection involved is reduced from 1 in over 1,000,000,000,000 to 1 in 42.

In conclusion, it should be pointed out that a large class of problems that are associated with perception, cognition, learning, decision making, prediction and control, can be viewed in principle in terms of problems of regulating uncertainty. This fact gives the concept of variety a particularly important validity as it offers a powerful tool for approaching issues that range from aspects of biological adaptation to problems of management and of effective regulation in general.(56)

C-5 Open and Closed Systems

The distinction between open and closed systems(57) is the distinction between viable systems that maintain a coherent integrity by interacting with an environment through an active exchange of material components, and inert matter, which inherently tends to become uniform with its surroundings. The distinction emerged in biology in the face of what had seemed to be an essential contradiction between phenomena observed in the life sciences and the laws of thermodynamics formulated in physics. The issue was that of reconciling the characteristics of biological organisms and evolutionary processes with the second law of thermodynamics and the concept of entropic equilibrium.

Living organisms are associated with a condition of matter in which order and structure are maintained in a process of dynamic equilibrium by which a specific "steady state" is preserved. Furthermore, phenomena of growth and evolution manifest the fact that such orderly processes are not only capable of continuously maintaining themselves, but are also capable of a transition toward a progressive increase in order and complexity of organization. In fact, theories of evolution since Darwin and Spencer implied a view of the world in which matter was seen to evolve from less towards more organized forms. There were moral and philosophical interpretations involved as, in general, this view "placed emphasis on progressive evolution, with complexity and differentiation generally associated with goodness and value."(58)

Biological-evolutionary thinking seemed to clash with developments in physics, in particular with the second law of thermodynamics, which maintained that for physical systems a quantity called entropy will always increase leading to a time-independent state of entropic equilibrium. In such a state, all activity would cease to exist and all energy differentiation would level out. In terms of statistical mechanics, the increase in entropy was seen as proceeding in a direction in which eventually all states of matter would become equiprobable, thus "the tendency towards maximum entropy or the most probable distribution is the tendency to maximum disorder."(59) According to the second law of thermodynamics, therefore, the general trend in physical universe is towards dissipation and irreversible degradation of energy, tending towards an ultimate state of thermodynamic equilibrium characterized by an even distribution of low temperature, a condition in which all processes would come to an end that was actually called a "heat death." By implication the formation of complex order and increase in organization seemed paradoxical in a universe that was regarded as essentially running down.

The contrast with the coherence and evolutionary characteristics of the biological world was sharp, and while the second law of thermodynamics had been established on firm ground, the fact remained that life processes did show the properties of building up order and an ever higher differentiation of complexity and organization. Such properties seemed so striking, in fact, that from "the earliest time in human thought some special non-physical or supernatural force (vis-a-vis entelechy) was claimed to be operative in the organism."(60) This very same attitude was taken still quite recently by Driesch, for example, in his attempt to remove the difficulties mentioned above. Driesch was arguing that biological growth processes, and specifically the property of equifinality which seemed to contradict the laws of physics, could be only explained by assuming the operation of vitalistic forces in governing biological activity.(61)

Bertalanffy, however, was able to clarify the seeming paradox by observing that the laws of thermodynamics had been formulated with regard to closed systems which are energetically isolated from the world. They are thus inapplicable to the case of living organisms which are, in principle, open systems maintaining a continuous exchange of matter with their surroundings. The living organism, as Schrödinger has pointed out,(62) feeds in effect on "negative entropy." It is continuously importing complex organic substances and freeing itself from its own, unavoidable, entropic products. This essential property of "openess" relating to the continuous metabolic exchange of materials with the environment could thus explain the capability of maintaining an orderly and complex structure, and the fact that "living systems, maintaining themselves in a steady state, can avoid the increase of entropy, and may even develop towards states of increased order and organization."(63)

The articulation of the principle of open systems removed the apparent paradox that seemed to exist between physics and biology in that it showed that the laws of thermodynamics were relevant to a domain of systems different in kind from those encountered in biology. At the same time, it was made clear that an extension and generalization of these laws were needed so that they would eventually cover the case of open systems as well. Such a generalization was actually achieved and is associated with Prigogine and his colleagues,(64) who introduced the effect of metabolic exchange into the equations of entropic equilibrium, thus extending the second law into a version applicable to both closed and open systems.

According to Prigogine,(65) the entropy variation dS during time dt for an open system that exchanges energy and matter with its surroundings can be written as:

$$dS = d_eS + d_iS$$

where d_eS stands for the entropy flow from the environment and d_iS denotes the production of entropy due to irreversible processes internal to the system. The second law states that d_iS can never be negative ($d_iS \geqslant 0$). In an isolated system $d_eS = 0$ and we get the obvious result that for all physical closed systems the entropy increases irreversibly, namely:

$$dS = S \geqslant 0$$

In an open system, however, Prigogine points out, while d_iS is always positive, d_eS may be either negative of positive with the result that "during evolution a system may reach a state where entropy is smaller than at the start."(66) Such a state can in fact be maintained as long as the general condition

$$d_eS = -d_iS \leqslant 0$$

applies. In other words, "in principle, at least, if we supply a system with a sufficient amount of negative entropy flow, we can maintain the system in an ordered state."(67)

Prigogine's work is associated with the relatively new field of nonequilibrium thermodynamics which has been particularly significant in throwing new light on processes associated with open systems and particularly in extending the thermodynamic model to problems of evolution. This work removed earlier ambiguities resulting from the partial applicability of the second law in its original form and has offered a coherent framework which integrates the dynamics of entropic processes in closed systems and in situations of "nonequilibrium" where orderly structures may appear that are able to progress to novel dynamic regimes of new and higher complexity.

By implication one can speculate about a view of a fundamentally regenerative universe in which entropic processes tending to the state of maximum disorder are encountered by tendencies towards situations in which order is created locally, and properties of coherence, structure and self-organization appear. In a sense, observable patterns of behavior in the universe at large may be regarded as the outcome of a balance created by these two opposites, and if this is the case, we are brought by contemporary arguments of modern physics face-to-face with some of the most ancient of human mythologies.

C-6 Entropy, Information and Organization

Facing the complex world around him, the notions of order and chaos have intrigued man since time immemorial. This fact found expression in various ancient mythologies, particularly in those dealing with the problem of creation. The biblical story of Genesis, for example, offers a clear illustration of the ancient concept of order and of the direction that orderly processes were assumed to take. Order emerged by the differentiation of chaos, homogeneity and sameness, into variety, coherence and structure.

Homogeneity is the one extreme and order is the other, an idea which is quite close to the notion of entropy and the direction of entropic processes, of which we had a glimpse in the previous section. Thus, in a sense, the concept of entropy, and particularly its expression in statistical terms, has given a rigorous definition to that which has been held intuitively for long. The modern concept, however, provides a precise mathematical definition to the relative conditions of "order" and "disorder," and it has an important formal link to the contemporary definition of information and subsequently it also bears on the definition of organization. These notions and how they relate will be reviewed below.

The concept of entropy was developed in relation to the observation that there is a general tendency in physical systems for energy differentiations to even out. If two bodies of different temperatures are placed in contact, the tendency is for heat to flow from the warmer to the cooler body in a process that will continue, if left undisturbed, until the temperatures are equalized. Around 1850, this observation was generalized by Clausius into what came to be known as the second law of thermodynamics which stated, in principle, that heat cannot be transferred from a cold to a warmer body without the introduction of an outside source of energy.(68) In this relation, Clausius introduced the term entropy to account for the energy disbalance which results in irreversible heat loss. This entropy, he maintained, will always tend to increase.

In classical physics, the quantity of entropy is measured in relation to the absolute zero point of temperature (approximately -273°C), at which point the entropy of any substance is given as zero. As heat is introduced, the entropy increases and the rate of its increase is obtained by computing the ratio of all the small increments of heat which were supplied, by the absolute temperature at which each was supplied, and then integrating all these small ratios from the temperature of absolute zero. The general expression takes the form:

$$S = \int_{o}^{T} \frac{dQ}{T}$$

where S stands for entropy and dQ is a small increment of heat supplied at temperature T. The unit of entropy S is thus given in cal/C°.

A further refinement in the development of the concept of entropy occurred when it was linked to statistical notions of order and disorder as developed by the work of Boltzmann and Gibbs. The basic notion had to do with the recognition that heat can be discussed in terms of the motions of atoms. Hence, as Boltzmann had pointed out, as energy is degraded the atoms assume a more random, or disorderly, state and, consequently, entropy can be regarded as a measure of disorder. This measure is given as:

$$S = k \log D$$

where S denotes entropy, k is a constant of proportinality known as Boltzmann's constant, and D is a measure of the probability of the system being at a particular state of all the states that are possible. As Schrödinger points out, D can in fact be regarded as a "quantitative measure of the atomistic disorder of the body in question."(69)

Entropy, then, is expressed as the logarithm of the probability of a particular state, and by the terms of the expression, this probability rises proportionately to the rise of entropy. In other words, the most probable state is the state of maximum entropy, or maximum disorder, and this is the state to which all isolated physical systems tend. The increase in entropy is associated with the loss of distinctiveness, differentiation and order, or as Wiener had expressed it "in Gibbs' universe order is least probable, chaos most probable."(70) This is precisely the source of the notion of the universe moving towards a "heat death" and the particular significance of the concept of open systems, vis living organisms, which as we have seen literally feed on "negative entropy," thus making it possible for organization to increase at least locally and temporarily.

The precise meaning of the concept of negative entropy can be obtained, as Schrödinger had shown, directly from the equations for entropy. The essence of his argument is that if D is taken to express a measure of disorder, its reciprocal 1/D could be regarded as a direct measure of order. And since

$$\log 1/D = -\log D$$

we could obtain for the equation of entropy:

$$-S = k \log(1/D)$$

or:

$$-(\text{entropy}) = k \log(1/D)$$

The conclusion, in Schrödinger's words: "entropy, taken with the negative sign, is itself a measure of order."(71)

As it turned out, a similar conclusion was reached with the development of the contemporary mathematical theory of communications. In its original form proposed by Hartley, a quantity of information was defined in terms of a successive selection of signs from a given list of possible signs.(72) According to Hartley, for a measure of N signs chosen from a repertoire of S signs, where the total number of possible combinations is S^n, a "quantity of information" H, can be expressed as:

$$H = N \log S$$

As Wiener later pointed out, statistical notions are particularly important in connection with the definition of information in that "the transmission of information is impossible save as the transmission of alternatives."(73) Consequently, the idea of entropy as defined in statistical mechanics provides a useful concept for the definition of information which in its current form was developed by Shannon.(74)

As is the case in Hartley's definition, an amount of information is expressed in relation to the choice of a particular message out of a given source of signs. It thus takes a similar form where information is measured by the logarithm of the number of available choices. In the statistical definition, however, these choices are expressed in terms of the probabilities which govern the selection of successive signs. Thus, for a set of n independent signs with probability of selection P_1, P_2 ... P_i ... P_n an amount of information H is defined as:

$$H = -\sum_i P_i \log P_i$$

where P_i is the probability of occurrence of a selection i out of the possible n. As we have seen earlier with regard to the concept of variety, the use of logarithms is particularly convenient because of the multiplicative characteristics of accumulating probabilities and the base 2 is chosen because it provides, directly, a standard unit associated with binary selection. The quantity of information itself is given as an average.

An expression similar to the one defining entropy can be used in the case of information because, essentially, the patterns of signs in a message can be regarded as a form of organization. Moreover, in the case of entropy, as we have seen, organization deteriorates as the system moves towards a more probable state. Similarly, the amount of information conveyed by a sign decreases as the probability of its occurrence is increased. This is the key to the relation between the two concepts and in general as a system gains in entropy it "loses" information in the sense that the more disorganized it is, the more homogenous, the less information it conveys. When the system reaches a state of maximum entropy, no information is conveyed by it at all. This is the reason for regarding information as the negative of entropy. As Wiener summed it up: "Just as entropy is a measure of disorganization, the information carried by a set of messages is a measure of organization. In fact, it is possible to interpret the information carried by a message as essentially the negative of its entropy, and the negative logarithm of its probability. That is, the more probable the message, the less information it gives."(75)

A particularly elegant means for expressing the notion of organization was offered by von Foerster(76) who suggested using Shannon's concept of redundancy which is given as:

$$R = 1-\frac{H}{H_{max}}$$

where H expresses the actual variety of a source and H_{max} is the maximum possible variety of the same source. As a result, von Foerster points out, the measure of order would conveniently assume values between zero and unity. Thus, when the system is in maximum disorder, the actual variety equals the maximum variety and R will be zero. In the other extreme, when the system is completely orderly, namely when there is no uncertainty about it, the entropy is zero and R assumes the value of 1.

As a final note it should be pointed out that beyond the technicalities of their definitions the concepts of entropy, information and organization have contributed substantially to shaping the contemporary view of the world. In particular the notions of entropy and order, by defining two major opposite directions that natural processes can take, towards an increase in randomness on the one hand and toward the evolution of order on the other, have provided an important conceptual guiding principle. They have an obvious effect on basic notion of progress and their general philosophical and moral impact have been profound. For example, Fuller has suggested that "the mind of man seems to be the most advanced phase of antientropy witnessable in the universe,"(77) and that the "function" of humanity in the universe can be interpreted accordingly. A somewhat similar notion is also voiced by Wiener when he suggests that in the face of entropic forces and ultimate decay, "our main obligation is to establish arbitrary enclaves of order and system."(78)

C-7 Feedback and Self-Regulation

As we have seen, a significant property of viable, or open systems, is manifest in the ability to resist an entropic drift and maintain an orderly structure stable. Such systems survive by virtue of a continuous intake of energy and/or physical material from which their fabric is being continuously synthesized. They interact with their environment in a dynamic process of importing and exporting essential substances, at the same time maintaining constant the ratio of critical ingredients in their flow of metabolic exchange. In spite of environmental perturbations, they preserve their internal composition and resist critical deviations from the conditions by which their surivival is defined.(79) In this regard, we have also seen how the extension of thermodynamic theory to cover open systems made it possible to account for such properties in terms of physics.

Taking a global viewpoint, it is clear that what we perceive as the individuality of a system, an organism, for example, is not defined by the specific composition or particular properties of its material components. Rather, it is the result of a continuity of processes, the consistency of a dynamic pattern, or, what amounts to the same thing, a stability of an organization. In this sense, cybernetics points out, the stability of a viable organization depends upon the operation and specific structure of information-related processes performing essentially a regulation function. Such regulatory mechanisms operate in all levels of the organism often in a highly complex and interdependent manner.

An archetypal regulating mechanism, long familiar to servo-engineers, but upon which cybernetics has cast a new light by drawing attention to its broad validity, is associated with feedback regulation. The related theoretical foundation is quite solid and the mathematical apparatus available is well developed, especially in relation to servo-mechanisms and various other aspects of control theory.(80) The literature which bears upon the subject matter, in one way or another, is extensive and, therefore, only a very brief account of some central issues will be given below.

The basic notion is of regulating a process by the results of its actual performance. The mechanism depends on a structural arrangement by which output is being continuously monitored and a signal conveying a measure indicating its value is obtained. This signal is fed back to an apparatus designed to adjust an input signal so that a desired output can be maintained or amplified, depending on a desired outcome.

The essence of feedback regulation, then, is of informational coupling by virtue of which an actual output is compared with some given standard. Such a standard specifies the value for an operational criteria pertinent to the system's performance and it can generally be interpreted as a system's goal. A goal of the system at large, or of any of its subcomponents, depending upon the level of resolution at which the feedback loop, is identified.

Realization of the universal significance of feedback mechanisms to regulation and the fact that such mechanisms exist in a wide variety of systems in technology and in the biological world, characterized the early days of cybernetics. In this respect an important step was taken by Wiener, Bigelow and Rosenblueth when they made a general distinction between purposeful and non-purposeful types of behavior showing that purposeful behavior could be clearly identified with mechanisms of feedback nature.(81) Wiener and his colleagues identified the standard by which an output is adjusted with a system's purpose, thus giving the notion of teleology a novel interpretation. The concept, which was previously used in a sense implying a "final cause," has now obtained a new and more precise meaning restricted by an association with a specific mechanism, controlling behavior by adjusting the difference between an actual output and its intended value. "Teleological behavior," they concluded, "thus becomes synonymous with behavior controlled by negative feed-back."(82)

This development was particularly significant as by identifying purpose with the effects of behavior, rather than with a particular kind of system, the ground was laid for stressing the essential similarity between purposeful behavior in animals and machines. This similarity exists on the specific level relating to the informational structure of feedback mechanisms, but it is also manifest on the general functional level of a "loop of action" incorporating sensory capabilities with control apparatus as well as affectors suitable for the performance of specific tasks.(83)

To be "purposeful," the arrangement entails a goal (the "standard" referred to above), and as Pask points out,(84) an important distinction can be made between goals which are inherent to a system and goals which are assumed with respect to a system by an observer who watches its behavior. In the first case, the goal is prescriptive in the sense that it is built into a system, some homing device, perhaps, by its designer. In the second case, on the other hand, the goal is descriptive in that it is projected by an observer as he gives an interpretation to the behavior of a complex system, a living organism or a society, for example, the behavior of which he may be trying to understand.

Similarly, a goal can be unambiguous, a well specified algorithm, as in the case of the simple thermostat, or it can be underspecified and open-ended as is typical in the case of evolutionary processes. This distinction is important because it allows an extension of the use of the basic feedback model to processes which, due to their complexity, dynamics, or both, are inherently fuzzy.(85)

Depending on the effect of a feedback coupling on the behavior of an output, a distinction is made between two classes of feedback systems. These are commonly referred to as negative and positive feedback respectively. Negative feedback is associated with the case in which a measurement of the actual output is compared with its desired value and the difference is used to modify the output in a way which forces it to approach the desired value. In the case of a positive feedback, on the other hand, the output value is coupled back in a manner which amplifies the original input signal.

A typical representation of a simple feedback loop is given in Figure C-3, where some active element, which could stand for a rudder in a servo-mechanism, for example, is being regulated.

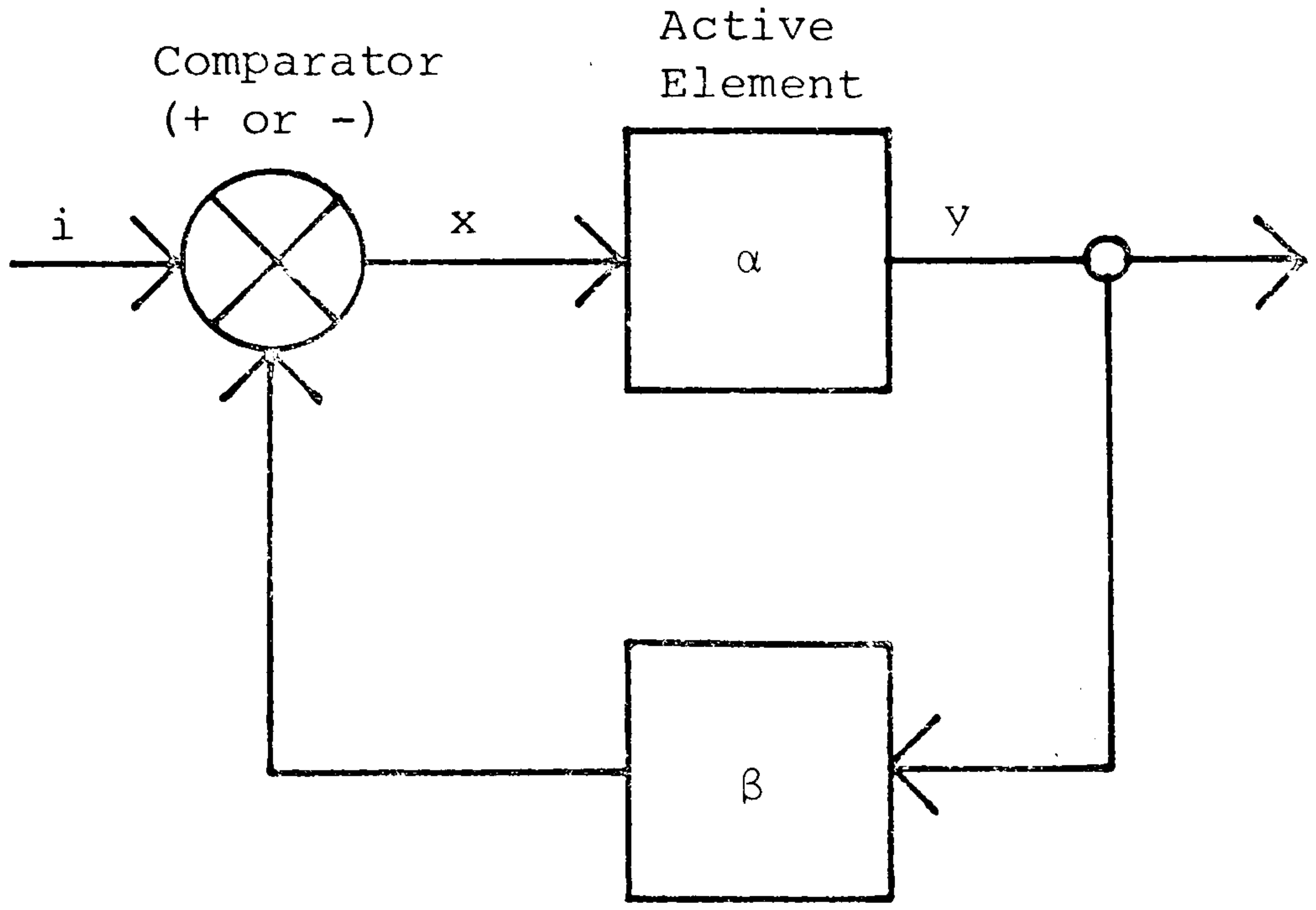

Figure C.3. A Simple Feedback Loop

A control signal x is derived from the input i which sets an operational standard. α represents the transfer function across the active elements so that the output y is a function of the control signal and the transfer function α. I.e., $y = f(x;\alpha)$. Similarly, β represents a transfer function by which the value of the output y is modified before it is compared with the original input. Focusing on the comparator, we distinguish between two cases as shown in Figure C-4 below:

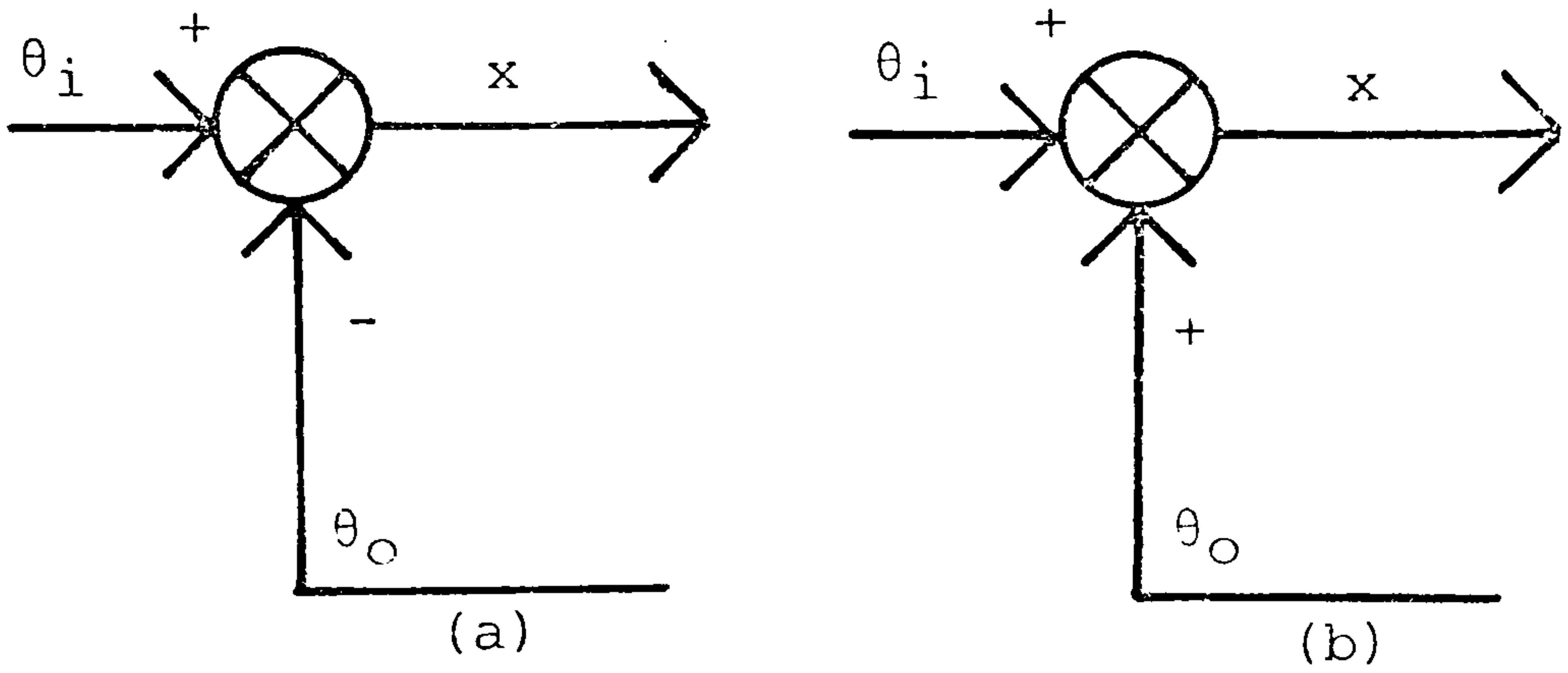

Figure C.4. Negative and Positive Feedback Loops

The first, (a), represents a negative feedback in which the control signal x is obtained by the difference between the input θ_i and the output θ_o, namely $x = \theta_i - \theta_o$. In the case of a positive feedback, depicted by (b), the control signal is obtained by adding the output value θ_o to the input θ_i, i.e., $x = \theta_i + \theta_o$, with the result that the original input value is being continuously amplified.(86)

In general, negative feedback is inherently stabilizing as it seeks to correct for deviations from a given standard. It is typically associated with goal seeking and homeostatic mechanisms. The operation of such a negative feedback, as Wiener pointed out, "may be as simple as that of a common reflex, or it may be a higher order feedback, in which past experience is used to regulate not only specific movements but also whole policies of behavior."(87) From a behavioral viewpoint it may thus relate to simple automatic actions, to the operation of conditioned reflexes and even to higher forms of learning. In contradistinction, positive feedback causes deviations and instabilities to amplify. It is usually associated with a self-reinforcing, accelerated departure from an initial condition in which case "an action builds a result that generates still greater action."(88) It is typical to processes of growth or decay such as are found in an unchecked population increase, the spread of an epidemic, certain cases of organic decomposition, and so forth.

Negative and positive feedback mechanisms may interact mutually to produce complex patterns of behavior as is typical to cases in which a regenerative growth, caused by a positive feedback loop, is checked by being coupled to a negative one. A simple illustration can be found in the cyclical interaction of prey and predator populations in which a significant increase of number of animals of a species preyed upon leads to an increase in number of their predator's population with the inevitable result that the number of prey animals is reduced and consequently there is a reduction in the rate of increase of predators as well.(89)

In the realm of economic affairs, to pick an additional example, Forrester has shown that similar mechanisms underline the behavior of certain business cycles. He demonstrates the point in a typical case of an increased sales rate which produced higher revenues, that lead to a higher sales budget and greater sales effort, followed by a further increase in sales. This regenerative cycle is reversed, however, when sales rate reaches a point at which it exceeds production capacity. An order backlog accumulates, resulting in delayed deliveries which make the product less attractive to buyers. The sales rate goes down, and so on . . . (90)

Feedback mechanisms rarely exist as in the simple single loop of Figure C-3. A dynamic viable system of even a moderate complexity consists of a multitude of such loops, coupled together and interacting in a complex fashion. As a whole system, it reveals a web-like structure of multiple loops, at times following a scheme of a control hierarchy in which some such loops are subordinate to the purpose of higher level ones. Techniques for studying systems behavior by analyzing the underlying structure of their feedback mechanisms are well developed and are due in particular to Forrester's work.(91)

Mechanisms of negative feedback have been studied extensively with specific regard to problems of control. In this context the notion of self-regulation has emerged as all-important. The idea relates to the fact that in mechanisms which operate by the negative feedback scheme, the act of going out of control, in itself, triggers the appropriate action which restores stability. In other words, deviations, as long as they are not fatal, are automatically compensated for because they are coupled to a control mechanism in a way which causes it to act immediately, automatically, and proportionately to the deviation from a norm. This is quite different from reacting after the fact. Beer in particular has strongly emphasized this point, its fundamental distinction from a simple-minded notion of control as a coercive action, and its implication to the general field of management.(92)

A classical example for self-regulation can be found in the operation of Watt's governor which regulates the supply of steam in a steam engine. The device operates in such a way that an increase in the speed of revolution of the engine causes a mechanical movement in the controller which results in reducing the input of steam, thus causing the speed to come down. Deviations from a desired speed cause a direct compensation and the speed is kept stable.

The Watt's governor is a simple mechanical device but the same principle of self-regulation which it embodies can be found in more complex systems and in various levels of reality. Thus in addition to typical servo-controls,(93) the principle relates to physiological functions of various kinds,(94) to certain behavioral aspects of organisms, simple or complex,(95) to industrial and managerial systems,(96) to various manifestations of social and economic behavior,(97) and to problems associated with ecological stability.(98) In linking the operations of various organizations, such mechanisms offer a unifying principle, and in this sense it is possible to regard our total environment as a vast complex of semi-autonomous, mutually interacting and self-stabilizing feedback mechanisms.

C-8 The Self-Organizing System

The concept of an open system interacting with its environment, the concept of order in the sense of Section C-6, the concepts of negative entropy and of the relativity inherent in an observer's interpretation of a system's purpose, all combine in the idea of self-organization. An extensive discussion is due to Ashby,(99) Beer,(100) Pask,(101) and von Foerster.(102)

The idea refers to a dynamic system which is non-stationary in the sense of Pask.(103) Its dynamics is such that it compels an observer who watches it over an interval of time Δt, to conclude that it generates spontaneous organization. In other words, the case in point is of a given universe a local region of which shows an activity that is accompanied by an observable change in organization. From the viewpoint of its entropy, von Foerster argues,(104) the activity in such a region can be characterized by one of the following three conditions: its entropy can increase with time, in which case it behaves like a typical thermodynamic system; it can remain unchanged, in which case it acts like a mechanical system; or else its entropy can actually decrease, implying an increase in organization, and the system will be called self-organizing. Thus, to be self-organizing, a system with entropy S_s that changes over time t must satisfy the condition

$$\frac{\delta S_s}{\delta_t} < 0.$$

That this condition holds implies an activity and an increase in organization which, according to Ashby,(105) may have the following meaning. Firstly, it may mean a change from a disorganized to an organized condition. For example, parts which were previously separated may be joined to form an integrated whole. Ashby uses as an illustration the development of connectivity in an embryo's nervous system, but the development of a roads network over a new territory, the expansion of a communications system to connect previously isolated centers, and even certain types of political integration may illustrate the point equally well.

Secondly, Ashby points out, self-organization may be used to convey a qualitative meaning as when we talk about an organization the performance of which is improving. It is becoming a "better" organization. A typical example is a student who is learning a skill and is progressively improving his proficiency in it. But on a more general level we may regard evolution, in the specific sense of an organism or a specie, as well as in the sense of a general trend,(106) essentially as being a process of this kind. All these cases portray systems which are self-organizing, in that by and large they develop in the direction of becoming "better" organizations. Problems associated with adaptation and evolution can thus be interpreted in terms of organizations which, over time, become more efficient or better fit for the task of survival in a particular environment.

This last remark is particularly significant because it bears upon the very essence of the qualitative notion of good or bad organization. This notion was given a rigorous definition by Ashby(107) and Sommerhoff.(108) The central issue of their argument is that an organization can be judged to be faulty or effective depending on how successful it is in maintaining conditions which are essential to a system's existence. The idea implies a goal, defining the "focal conditions" for the organization's successful survival. It also implies some environmental perturbations which threaten this goal. Given such a set of disturbances and a goal which defines a stable condition, "an organization is good if it makes the system stable around an assigned equilibrium."(109) There is a strong connotation of relativity involved as changing environmental circumstances may require a significant change in an organization if it is to remain effective.

With this in mind, self-organization may generally be regarded as a process of "structural adjustment to a set of disturbances within the context of a set of overriding goals."(110)

The general concept of organization itself is defined with respect to a set of constraints acting on a given universe of possibilities. We say that a group of variables form an organization when there exists some specific relations which define their interactions. Such relations act in effect as constraints which reduce the total number of possible configurations that the variables could assume if they were acting independently. Moreover, when we talk about an organization forming within a particular systemic boundary, we rely on a mental act of discovering a growing number of such fundamental relations operating between the system's variables. This view of organization as the actual restricted subset of a range of possible behavior has emerged directly from the logic of information theory. It provides the core of von Foerster's argument for using the information theoretic concept of redundancy as a measure of organization.

As we have seen in Section C-6, von Foerster has shown that the redundancy of a system, taken as a measure of organization, can be computed by obtaining the ratio of the system's actual variety to its maximum variety and subtracting this ratio from unity. The resulting measure thus assumes a relative value that ranges between zero and one.

Using this specific concept of organization and noting that in a self-organizing system we would expect order and organization to increase with time, von Foerster has gone on to develop an elegant definition for a self-organizing system.(111) According to this definition, a system is a self-organizing system if and only if the rate of change of its redundancy is positive. Namely

$$\frac{\delta R}{\delta t} > 0.$$

The immediate implications of such a condition are clear. From a behavioral point of view, the fact that the rate of change of a system's redundancy remains positive means a richness of behavioral patterns that the system can continuously exploit. There is always room allowed for change and for new behavioral manifestations. New degrees of freedom remain open and therefore the behavior of such a system cannot be entirely and precisely pre-specified. From the more general viewpoint of a theory of equilibrium, this behavioral richness would mean that the system has many points of equilibrium at which it is stable. Unlike a simple pendulum or a marble in a concave vessel, for which equilibrium is specified by a single point, such a system is characterized by a large region within which it can be stable. In other words, a self-organizing system always occupies only a subset of the total number of stable states that are potentially open to it. It is ultrastable in the sense of Ashby,(112) and as it seeks equilibrium it shows a dynamic and versatile behavior. In fact, moving towards equilibrium, it performs acts of selection in that it "rejects" those states which are not stable. It may thus appear to an observer who has the system's goal in mind as though it was making intelligent decisions in the process of seeking stability.

The introduction of an observer is an essential feature of the discussion of organization, the reason being that the identification of an organization, in the first place, depends on an observer selecting a specific set of attributes that he deems relevant with respect to a particular universe of discourse. The notion of organization is therefore a relative notion as it depends on a specific observer, his observational capabilities and purpose, and his relation to a specific part of the world. This relation, Pask has stressed,(113) obtains a special meaning with respect to a self-organizing system. The point is that when he is faced with a self-organizing system, an observer may find that in order to make sense of its behavior he will have to continuously change his frame of reference. This is another way of saying that because the system is typically involved in processes of development or evolution, the observer will have to change the original criteria of his observation if he is to "Keep Up" with the system's dynamic behavior.

There is a fundamental structural uncertainty involved which is typical to interaction with the "fuzzy" systems that are encountered in biology, psychology and the social sciences. Because of it, the observer may have to continuously change the boundaries of the universe of his observations in order to account for new stages in the system's development. Similarly, he may have to increase the scope of his language, perhaps by stratifying it, in order to obtain a description that is rich enough to account for new manifestations of the processes under observation, as they unfold. A self-organizing system, Pask points out, cannot be approached with the assumption that conditions defining its existence will remain invariant for any length of time. No unique, pre-specified formula for controlling it can be effective, and the process of interacting with a self-organizing system must therefore be essentially conversational in nature. It is characterized by the fact than an observer must continuously adapt his procedures so that "as a result of the interaction some continuously changing descriptive model is built up."(114)

The concept of self-organization has brought about a significant reorientation in the scientific view of complex systems and particularly of the evolution of stable organizations in complex environments. According to the current view, any system of significant complexity, given time and an unvariable set of environmental constraints, will show a typical self-organizing activity in the sense of settling to local stabilities which are particularly well adapted to those specific constraints. The implications to problems of the origin and evolution of life on earth, for example, are all important. As Ashby suggests, if the system in view has been in existence as long, and is as complex as the terrestrial environment, "then nothing short of a miracle could keep the system away from those states in which the variables are aggregated into intensely self-preserving forms."(115)

C-9 The Organization of Complexity

Central to the system's view of the world is the concept of an organizational hierarchy in which systems nest in a recursive fashion. In such a hierarchy, lower level systems form sub-components of more inclusive higher order ones.

From a system theoretic viewpoint this means that a fundamental property of systems is manifest in the fact that any variable that is identified as a sub-component in a system can itself be regarded as a system and similarly the system of which it is a part can in turn be regarded as a component in yet a larger system. But notwithstanding such notions stemming from the logic of a general theory of systems, there is a definite sense in which we intuitively regard the world as a hierarchy extending from the simplest forms of matter to the highest forms of life. It is quite common, for example, to find descriptions of physical matter which stress an hierarchical order of distinctive levels progressing from atomic sub-components to atoms, molecules and crystals. Similarly, biological organisms are often described as occupying a place in a hierarchy between higher levels of populations and whole ecologies and lower levels associated with cells and organic macro-molecules respectively.

According to Simon,(116) there seems to be a convincing physical basis for the fact that evolution in complex systems proceeds in a process that favors the formation of hierarchical structures. Simon has shown that the time required for the evolution of complex structures will be shortened considerably if it will take place by stages where each stage forms a stable sub-system constituting a layer in a hierarchy. Computing relative assembly time for systems with a large number of components, Simon's results indicate that under certain probabilistic constraints of association and decomposition, a system of n components, organized in layers of stable sub-assemblies, will be more resistent to perturbations, and will thus evolve more quickly than will a system containing the same number of components that is not organized hierarchically. Hierarchical organizations of semi-autonomous stable sub-assemblies thus seem to be a fundamental property of complex systems and examples for manifestations of "stable levels" are typically associated with atoms in a complex substance, cells in a biological organism or family units in a social system. As Simon concludes, "Nature is organized in levels because hierarchic structures--systems of Chinese boxes--provide the most viable form of any system of even moderate complexity."(117)

While levels in a hierarchy consist of stable subassemblies, these are not entirely free from interaction with other levels that are immediately higher or lower. The difference is in the strength of such interactions. They are stronger within each level and weaker between them. In fact, the relative strength of relations and their distribution with respect to one another gives the concept of a distinct level its meaning. Thus, components that interact to form a specific level are characterized by bonds that are especially strong. It is the relative strength of such relations which allows for a definition of boundary conditions and makes the individual integrity of a level stand out against the background of its environment.

While a typical level in a hierarchy may include a few assemblies which are characterized by similar intensities of internal relations, and are coupled horizontally by weaker interactions, a vertical hierarchy will show a progressive reduction in strength of interactions as we move from lower to higher levels. A particularly clear example is furnished by the hierarchical structure of matter in which each level in the hierarchy is associated with a specific intensity of energetic interactions. Thus, by far the most intense forces are found in the sub-atomic level in which basic particles interact to form the nucleus. The intensity of forces in chemical bonds forming molecules are very significantly lower, and they are much lower still in the structures combining organic macro-molecules.(118)

In general, then, complex dynamic systems tend to exhibit a web-like structure in which hierarchical levels are distinguishable by the overall distribution of interactions of various intensities. Simon coined the term "nearly-decomposable systems" to characterize such systems in which weaker bonds operate between levels causing the appearance of hierarchies. He sums up this feature of reality as follows: "The world is a large matrix of interactions in which most of the entries are very close to zero, and in which, by ordering these entries according to their order of magnitued, a distinct hierarchic structure can be discerned."(119)

The concept of organizational hierarchy is particularly amenable to a definition in set theoretic terms.(120) In such terms a hierarchical structure is seen as a super-set containing a succession of ever more encompassing sub-sets. In general, a given level in a hierarchy will be defined as a set S such that

$$S = \{a_1, a_2, \ldots, a_n\}R$$

Where $a_1, a_2, \ldots, a_n$ are elements in a specific level and R denotes the set of all the relationships r_{ij}(i, j = 0, 1, ..., n) that operates between them. In a hierarchy, each element $a_1, a_2, \ldots, a_n$ is itself a set and S is an element in a larger set, corresponding to a higher level. As before, the intensity of R is lower between boundaries of successive sets.

An important aspect of "hierarchy theory" relates to the fact that in general levels are associated with particular properties. Each such level is characterized by unitary characteristics that are the synergetic result of its specific components and the interaction between them. As we change the resolution of observation and move up a hierarchy towards more inclusive higher-order domains, we encounter a progression of emerging new properties.

The emergence of such new properties with higher levels of organization has been variously referred to as "neo-genesis"(121) or "emergent evolution."(122) It relates to the transition from a component to a set or from a set to a super-set. In such new collective associations, synergetic properties may appear which do not reside in individual components, are unpredictable from the viewpoint of lower levels, and are interpretable only in the context of a reference frame provided by a higher level of integration. Even though the precise mechanisms may not yet be entirely understood, there is a definite sense in which evolution can be interpreted, from an organizational viewpoint, with respect to a structural hierarchy associated with a progressive increase in complexity and the respective emergence of new synergetic properties. Fuller, for example, expresses the underlying notion quite clearly when he refers to the universe as a "synergy of synergies." In his words, "There is a synergetic progression in Universe--a hierarchy of total complex behaviors entirely unpredicted by their successive subcomplexes' behaviors. It is manifest that Universe is the maximum synergy-of-synergies, being utterly unpredicted by any of its parts."(123)

The structural problem of hierarchical organization and the qualitative aspects of emergent properties associated with successive levels inexorably bear upon problems of language and description. Different levels of reality, and the contextual transition that comes with them, require alternative levels of description. Thus, for example, sub-atomic particles are described by terms different from those used in the description of molecules. Similarly, we use one level of description in dealing with a fertilized human egg, another in describing a human embryo, and yet another in portraying an adult human being.

The need for alternative levels of description is manifest in the structure of science itself.(124) Accordingly we have a differentiation of scientific fields into specialized branches reflecting specific levels of reality. In the physical sciences, for example, this is illustrated by sub-headings such as nuclear physics, molecular chemistry, molecular biology, and so forth. The hierarchy inherent in our description of the world has a deeper structural meaning, however, which emerges as a central issue in mathematical logic. Thus, Gödel's incompleteness theorum states that in principle no language can be complete and self-sufficient in itself. There are undecidable propositions encountered in a given language which cannot be answerable within the frame of reference of that language and can only be resolved by a higher order language. The implication is clear. Because of the incompleteness inherent in any language, an effective description of the world requires a hierarchy of languages in which each level serves as a meta-language to the one immediately below. Undecidable propositions encountered in a language that is associated with a particular level are thus resolvable only by a meta-language which is associated with the next higher level in that hierarchy.

Thus emerges an important relation which exists between the structure of the world and the structure of our description of the world.(125) Questions about the meaning of this relation are fundamental to epistemology and have provided, over centuries, a topic for an intense discussion in the philosophy of science. From the viewpoint of cybernetics, however, this relation is immensely important, especially with respect to problems of control. The point is that the organizational hierarchy typical to complex systems may, in fact, represent a hierarchy of control in which levels are associated with a particular set of constraints.(126) Such a control hierarchy can therefore be regarded as a hierarchy of command to which alternative levels of description are essential. Thus, effective control in complex systems depends on an appropriate match between functional levels in an organizational hierarchy and the corresponding levels of description by which control procedures are specified. The point has been discussed at length by Beer in the context of management,(127) and it is clearly expressed in Pask's learning theory,(128) in which experimental situations are characterized by a conversational interaction taking place in a stratified language of a control hierarchy.

In summary, complex dynamic systems typically possess a hierarchical structure. Such a structure seems to be essential for functional reasons which have to do with the system's viability and evolutionary potential. In addition, from a descriptive viewpoint, such complex systems are rendered comprehensible only by the use of a stratified language possessed of a hierarchy of successive and progressively more encompassing levels of descriptions.

NOTES TO APPENDIX C

SYSTEMS AND ORGANIZATION

1. Ackoff, R. L., "Games, Decisions and Organization," in _General Systems Year Book,_ 4 (1959); pp. 145-150.

2. See for example: Laszlo, E., _The Systems View of the World_. Likewise, Emery, F. E. (ed.), _Systems Thinking_ and Churchman, C. W., _The Systems Approach_.

3. Bertalanffy, L. von, _General System Theory_, p. 18.

4. Laszlo, E., _The Systems View of the World_, p. 11.

5. Bertalanffy, L. von, _General System Theory_, p. 18.

6. _Ibid_., p. 18. Bertalanffy has stressed that "these conditions are not fulfilled in systems, i.e. entities, consisting of parts in interaction."

7. Beer, S., _Platform for Change_, p. 27. Also p. 122. Beer points out the essentially systemic notions in Hegel's philosophy which emphasized the importance of "Internal Relations." See also _Decision and Control_, p. 244-245.

Bertalanffy traces systemic notions to Leibniz and in fact to as far back as the "mystic medicine of Paracelsus." He stresses, however, that "the necessity and feasibility of a systems approach became apparent only recently." _General System Theory_, p. 10-11.

8. Fuller, R. B., *Synergetics--Exploration in the Geometry of Thinking*, p. 3. Here and in his earlier writings Fuller has stressed the important implication of the idea of synergy to the understanding of the behavior of interrelated complexities.

9. Ackoff, R. L., *Redesigning the Future*, p. 13.

10. *Ibid*., p. 13.

11. *Ibid*., p. 12. Ackoff has emphasized that the two doctrines, though different, are compatible, and the one supplements the other.

12. See for example Reiser, O. L., *The Integration of Human Knowledge* and Siu, R. G. H., *The Tao of Science*.

13. Bertalanffy, L. von, Problems of Life: *An Evaluation of Modern Biology and Scientific Thought*, p. 11.

14. Ackoff, R. L., "System, Organizations, and Interdisciplinary Research" in *Systems Thinking*, Emery (ed.), p. 331.

15. For this definition and for a methodology developed for the description of systems behavior, see Holt, A. W., "Information System Theory Project," Technical Report No. RADC-TR-68-305, Rome Air Development Center (1968).

16. For a discussion of the problem of reality and mentalism see Cherry, C., *On Human Communication*, pp. 262-263.

17. Forrester, J. W., Principles of Systems, p. 1-1.

18. Fuller, R. B., Synergetics--Explorations in the Geometry of Thinking, p. 95.

19. Beer, S., Decision and Control, pp. 241-242.

20. Hall, A. D. and Fagen, R. E., "Definition of System" in General System Year Book, Vol. 1 (1956); p. 18.

21. Ibid., p. 18.

22, 23. Klir, J. and Valach, M., Cybernetic Modelling. For the symbols and definition, see pp. 27-29.

24. Pask, G., "The Cybernetics of Evolutionary Processes and Self-Organizing Systems," 3rd International Congress on Cybernetics, Namur (1961); p. 28.

25. Ashby, W. R., An Introduction to Cybernetics, p. 40. For a distinction between variables and parameters, see Ashby, Design for a Brain, Chapter 6. The general point is that "given a system, a variable not included in it is a parameter." Ibid., p. 71.

26. Pask, G., "The Cybernetics of Evolutionary Processes and Self-Organizing Systems," p. 29.

27. A survey of systems which uses a hierarchical method of classification is offered by Bertalanffy, General System

Theory, pp. 28-29, in pursuance of suggestions by Boulding. For other partial classifications, see Hall, A. D. and Fagen, R. E., "Definition of System" in General System Year Book, Vol. 1 (1956); pp. 18-28. And Ackoff, R. L., "Towards a Systems Concepts" in Systems Behavior, Beishon and Peters (eds.), pp. 83-90.

28. Klir, J. and Valach, M., Cybernetic Modelling, p. 45.

29. Ibid., p. 79.

30. Beer, S., Cybernetics and Management, pp. 12-19. Beer emphasizes the arbitrariness of such a classification which is a suggested one among the many possible.

31. Ibid., p. 18.

32. For a comprehensive account of the black box problem, see Ashby, W. R., An Introduction to Cybernetics. A brief but lucid account can also be found in Ashby, W. R., "General Systems Theory as a New Discipline" in General System Year Book, Vol. III (1958); pp. 1-5.

33. Ashby, W. R., An Introduction to Cybernetics, p. 86.

34. Ashby, W. R., "General System Theory as a New Discipline," p. 1.

35. Ibid., p. 3.

36. See Pask, G., An Approach to Cybernetics, as well as "The Cybernetics of Evolutionary Processes and of Self-Organizing Systems."

37. Pask, G., "The Cybernetics of Evolutionary Processes and of Self-Organizing Systems," p. 29.

38. *Ibid.*, p. 30.

39. Pask, G., An Approach to Cybernetics, p. 22.

40. *Ibid.*, in Appendix 2, pp. 121-122.

41. A typical example is furnished by the Heisenberg uncertainty principle. For a first hand account see, for instance, Heisenberg, W., Physics and Philosophy.

42. Distinction of structural and metrical uncertainty as quoted by Pask is attributed to Gabor and Mackay. See An Approach to Cybernetics, p. 20, as well as Appendix 1 on p. 121. For a comprehensive discussion, see also Pask, "Comments on an interdeterminancy that characterizes a self-organizing system," printed by Consiglio Nazionale Delle Ricerche, Rome (1965).

43. Ashby, W. R., "General System Theory as a New Discipline," p. 4.

44. Pask, G., An Introduction to Cybernetics, p. 43.

45. The discussion followed the rise of quantum theory and the dispute, for many years, centered around Einstein's views. See account in Einstein, A., Out of My Later Years; also a more comprehensive argument: Albert Einstein, Philosopher Scientist, Schilpp, P. A. (ed.). A first class account is also given by Bohm, D., in Causality and Chance in Modern Physics.

46. See Beer, S., Cybernetics and Management, p. 13.

47. Kohler, W., Gestalt Psychology, p. 29.

48. Beer, S. See Decision and Control, and especially Brain of the Firm.

49. Ashby, W. R., "General System Theory as a New Discipline," p. 1.

50. Beer, S., entry for "Variety" in Cybernetics of Cybernetics, a BCL publication No. 73-38, p. 80.

51. Pask, G., An Approach to Cybernetics, p. 26.

52. Arnold, P., Aton, B., Rosenfeld, D., Saxena, K. and von Foerster, H., "Diversity: A Measure Complementing Uncertainty," B.C.L. Report No. 84.

53. Ibid., p. 168. Von Foerster uses the term diversity for variety and the substitution of the term in the quotation was ventured only for clarity.

54. Beer, S., Decision and Control, p. 246-253.

55. Ibid., p. 252.

56. The key, of course, is in Ashby's "law of requisite variety." A particularly useful illustration with regard to problems of management can be found in Beer's Brain of the Firm.

57. See Bertalanffy, L. von, General System Theory, pp. 39-41, as well as Chapter 6. See also "The Theory of Open Systems in Physics in Biology," Science, Vol. III (1950); pp. 23-29. The terms open and closed systems are used with regard to energy exchange and should not be confused with systems that are closed to information in the sense of Ashby.

58. Laszlo, E., "A General Systems View of Evolution and Invariance" in General Systems Year Book, Vol. XIX (1974); pp. 37-43.

59. Bertalanffy, L. von, General System Theory, p. 39.

60. Schrödinger, E., What is Life?, p. 75.

61. Quoted by Bertalanffy, General System Theory, p. 40. In this regard, "equifinality" refers to a phenomena in which a final stage can be reached from different initial conditions.

62. Schrödinger, E., What is Life?, p. 61.

63. Bertalanffy, L. von, General System Theory, p. 41.

64. Prigogine's work is associated with the "Bruxelles School." Examples can be found in Prigogine, I., Nicolis, G. and Babloyantz, A., "Thermodynamics of Evolution" in Physics Today, November (1972), pp. 23-28 and December (1973), pp. 38-44. See also Prigogine, I. and Nicolis, G. "Biological Order, Structure and Instabilities" in Quarterly Review of Biophysics 4, 2 and 3 (1971); pp. 107-148. Comprehensive introductory accounts can be found in Katchalsky, A. and Curran, P. F., Nonequilibrium Thermodynamics in Biophysics as well as in Glandsdorf, P. and Prigogine, I., Thermodynamic Theory of Structure, Stability and Fluctuations.

65. Prigogine, I., Nicolis, G. and Babloyantz, A., "Thermodynamics of Evolution," Physics Today, November (1972); p. 24.

66, 67. Ibid., p. 24

68. Rothman, M. A., The Laws of Physics, pp. 157-160.

69. Schrödinger, E., What is Life?, p. 77.

70. Wiener, N., The Human Use of Human Beings, p. 20.

71. Schrödinger, E., What is Life?, p. 79.

72. For a comprehensive account of the mathematical theory of communication from its early developments to Shannon's formulation, see Cherry, C., On Human Communication, pp. 41-52.

73. Wiener, N., Cybernetics, p. 10.

74. Shannon, C. E. and Weaver, W., The Mathematical Theory of Communication, a general account is provided by Weaver in the first part of the book.

75. Wiener, N., The Human Use of Human Beings, p. 31.

76. Von Foerster, H., "Environments of Self-Organizing Systems" in Self-Organizing Systems, Yovitz and Cameron (eds.), pp. 31-50. See in particular p. 37.

77. Fuller, R. B., Utopia or Oblivion, p. 149.

78. McCulloch, quoting Wiener in "Recollections of the many sources of cybernetics," ASC Forum, Vol. VI, No. 2 Summer (1974).

79. Bertalanffy, L. von, "The Theory of Open Systems in Physics and Biology" in Systems Thinking, Emery, F. E. (ed.), p. 74.

80. See for example Wiener, N., Cybernetics, Chapter 4, pp. 95-115. Another comprehensive overview is given by Milsum's "Mathematical Introduction to General Systems Dynamics" in Positive Feedback, Milsum (ed.), pp. 23-65. A very readable account with specific respect to servo-mechanisms can be found in Porter, Servomechanisms. General references, however, are much too numerous to attempt a comprehensive review.

81. Rosenblueth, A., Wiener, W. and Bigelow, J., "Behavior, Purpose and Teleology," Phil. of Science, Vol. 10 (1943).

82. Ibid., p. 24.

83. For this issue, see Wiener, N., Cybernetics, p. 96.

84. For a discussion of goals and goal types, see Pask, G., "Some Mechanical Concepts of Goals, Individuals, Consciousness and Symbolic Evolution, especially pp. 2-6.

85. A major contribution to the concept of theory of fuzzy systems is due to Zadeh. See, for example, Zadeh, L. A., "Towards a Theory of Fuzzy Systems" in Aspects of Network and System Theory, Kalman and DeClairs (eds.). Also Zadeh, L. A., "Outline of a New Approach to the Analysis of Complex Systems and Decision Processes" in IEEE, transactions on systems, man and cybernetics, Vol. SML-3, No. 1, January (1973); pp. 28-44.

86. For a more detailed mathematical treatment, see Milsum, J. H., "General System Dynamics" in Positive Feedback, Milsum (ed.), pp. 23-65.

87. Wiener, N., The Human Use of Human Beings, p. 47.

88. Forrester, J. W., Principles of Systems, Section 1-5.

89. See for example Kerner, "Statistical Mechanics of Interacting Biological Species" in Bull. Math. Biophys. 19, p. 121 (1957).

90. Forrester, J. W., "Modeling the Dynamic Processes of Corporate Growth," reprinted from Proc. of the IBM Scientific Computing Symposium on Simulation Models and Gaming. December (1964).

91. Forrester, J. W., Principles of System, Industrial Dynamics, Urban Dynamics, and World Dynamics. Though the theory is quite impressive in its scope and logical consistency, there are some fundamental questions as to its useful application to systems which are exceedingly complex.

92. Beer, S., an example in Decision and Control, p. 263 and in Cybernetics and Management, p. 29.

93. See applicable material in Wiener, N., Cybernetics. Also Porter, A., Servo-mechanisms.

94. For a comprehensive review, see Stanely-Jones, The Kybernetics of Natural Systems. Also Rashevsky, N., Mathematical Principles of Biology, for example with regard to cell metabolism.

95. See Tinbergen, N., "Ethology (1969) in The Animal in Its World, Vol. II, pp. 130-156. Also Miller, G. A., Galanter, E., and Pribram, K. H., Plans and the Structure of Behavior.

96. See previous references to Forrester's work as well as Beer, S., "Towards a Cybernetic Factory" in von Foerster and Zope (eds.), Principles of Self-Organization, pp. 25-80.

97. For example Lang, O., Introduction to Economic Cybernetics, also Boulding, K., "Business and Economic Systems," as well as Dechert, C. R., "Integration and Change in Political and International Systems" both in Positive Feedback, Milsum (ed.).

98. Slobodkin, L. B., "Animal Population and Ecologies" in Positive Feedback, Milsum (ed.).

99. Ashby, W. R., "Principles of the Self-Organizing System" in Principles of Self-Organization, von Foerster and Zope (eds.), pp. 255-278.

100. Beer, S.: a) Decision and Control, Chapter 14; b) "Towards the Cybernetic Factory" in Principles of Self-Organization, von Foerster and Zope (eds.), pp. 65-81.

101. Pask, G.: a) "The Cybernetics of Evolutionary Processes and of Self-Organizing Systems"; b) "Comments on the Indeterminacy that Characterizes a Self-Organizing System"; c) "The Natural History of Networks" in Self-Organizing Systems, Youits and Cameron (eds.), pp. 232-260; d) An Approach to Cybernetics, pp. 102-108.

102. Von Foerster, H., "Environments of Self-Organizing Systems" in Self-Organizing Systems, Youits and Cameron (eds.), pp. 31-48.

103. Pask, G., see ref. 101 (d), p. 47.

104. Von Foerster, H., see ref. 102, p. 32.

105. Ashby, W. R., see ref. 99, pp. 266-267.

106. See Pask, G., ref. 101(d), p. 104.

107. Ashby, W. R., ref. 99, pp. 266-267.

108. Sommerhoff, G., Analytical Biology; also "Properties of Open Systems" in Systems Thinking, Emery (ed.), pp. 147-202.

109. Ashby, W. R., ref. 99, p. 263.

110. Beer, S., ref. 100(a), p. 355.

111. Von Foerster, H., ref. 102, pp. 38-39. Von Foerster further shows that a system with a positive rate of change of redundancy can be self-organizing either because the actual variety of its behavior is reduced or else because the maximum variety has increased. For the full mathematical argument, see ref. 102 above.

112. Ashby, W. R., Design for a Brain.

113. Pask, G., ref. 101(a-d), but especially (c).

114. Pask, G., ref. 101(c), p. 259.

115. Ashby, W. R., Design for a Brain, p. 233, but see also ref. 99, pp. 270-273.

116. Simon, H. A., "The Architecture of Complexity," Proc. American Philosophical Society, 106: 467-482 Dec. (1962).

117. Simon, H. A., "The Organization of Complex Systems" in Hierarchy Theory, Pattee (ed.), pp. 3-27.

118. On this point see Reiser, O. L., Cosmic Humanism, p. 214. Simon makes a similar point (ref. 117) in quoting Melvin Calvin in Molecular Coding Problems, Diane, R. M. (ed.), pp. 120-121, N. Y. Academy of Science (1967).

119. Simon, H. A., "The Organization of Complex Systems," p. 23.

120. See for example Grobstein, C., "Hierarchical Order and Neogenesis" in Hierarchy Theory, H. Pattee (ed), pp. 31-47.

121. *Ibid.*, p. 37 and also p. 47.

122. Reiser, O. L., The Integration of Human Knowledge, for example p. 271.

123. Fuller, R. B., Synergetics, p. 13.

124. Simon, H. A., "The Organization of Complex Systems," p. 24.

125. See Pattee's postscript to Hierarchy Theory, p. 135. A beautiful discussion about the relation between cognition and the structure of the world is offered by von Foerster in

"Biological Principles of Information Storage and Retrieval," B.C.L. Publication No. 150.

126. See Pattee, H. H., "The Physical Basis and Origin of Hierarchical Control" in Hierarchy Theory, Pattee (ed.), pp. 73-108.

127. See especially Beer, S., Brain of the Firm, in which a hierarchical control system for a company is developed and modeled after the hierarchy that is typical to the human nervous system.

128. See Pask, G., The Cybernetics of Human Learning and Performance.

APPENDIX D

THE ORGANIZATION OF BEHAVIOR

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D-1 System-Environment Interaction

From the outset, cybernetics is developed in behavioral terms,(1) and it approaches various manifestations of behavior from a very specialized viewpoint, namely, how these relate to the general idea of a system's effective viability. That is, a system's dynamic activity, which is associated with changes in its states, provides an observer with a stream of evidence which is interpreted as the system's behavior. The cybernetic viewpoint is concerned with the question of how such a behavior could be explained with respect to the general criteria of regulating the system's survival. The key issue is the nature of viable behavior: namely, of maintaining a particular stability, adapting to specific circumstances, or evolving as these change. This behavioral question is bound up with the problem of effective regulation and is inseparable from a discussion of mechanisms that affect, determine or control behavior.

From the viewpoint of effective regulation, a system cannot be studied in isolation. The notion is essentially a relative one and it emerges in the context of a particular set of parametric constraints which operate upon the system, defining the environment within which it has to survive. This leads to the conclusion that a system's behavior, and its regulation, have meaning only in the context of its interaction with an environment. The paradigm involved is therefore of two systems, an organism and its environment, for example, that are coupled to each other.

In this respect, an environment may be viewed as a complex of events in which local organizations are distinguishable as distinct patterns of semi-autonomous, self-stabilizing behavior. The differentiation between organization (qua organism) and environment is not always clear-cut. It is arbitrary in the sense that it depends on an observer's viewpoint, and it involves an ambiguity regarding the boundaries of the individual system (a psychological individual in the sense of Pask is a good example). Nevertheless, the idea underlines an understanding of behavior in so far as the environment is regarded as a source of disturbances, with respect to which regulating mechanisms operate to maintain a system stable around a particular equilibrium.(2) The conceptual distinction between a system and its environment is thus essential for the functional explanation of the operation of control mechanisms. This distinction is also inherent in the "system's view of the world," where it relates to a concept of reality that is regarded as a complex hierarchical organization in which systems nest recursively.(3) In such a hierarchy, each level constitutes an "environment" for the lower level that it contains.

A representation of a system-environment coupling is given in Figure D-1, in which a system S interacts with an environment En. The system's behavior is represented by an output x that is a function of environmental input y and the system's internal state S_i. Thus, in a typical dynamic situation representing such an interaction, the system's outputs and its internal states will change with time as a result of variations in environmental inputs or of the action of some internal optimization mechanism.

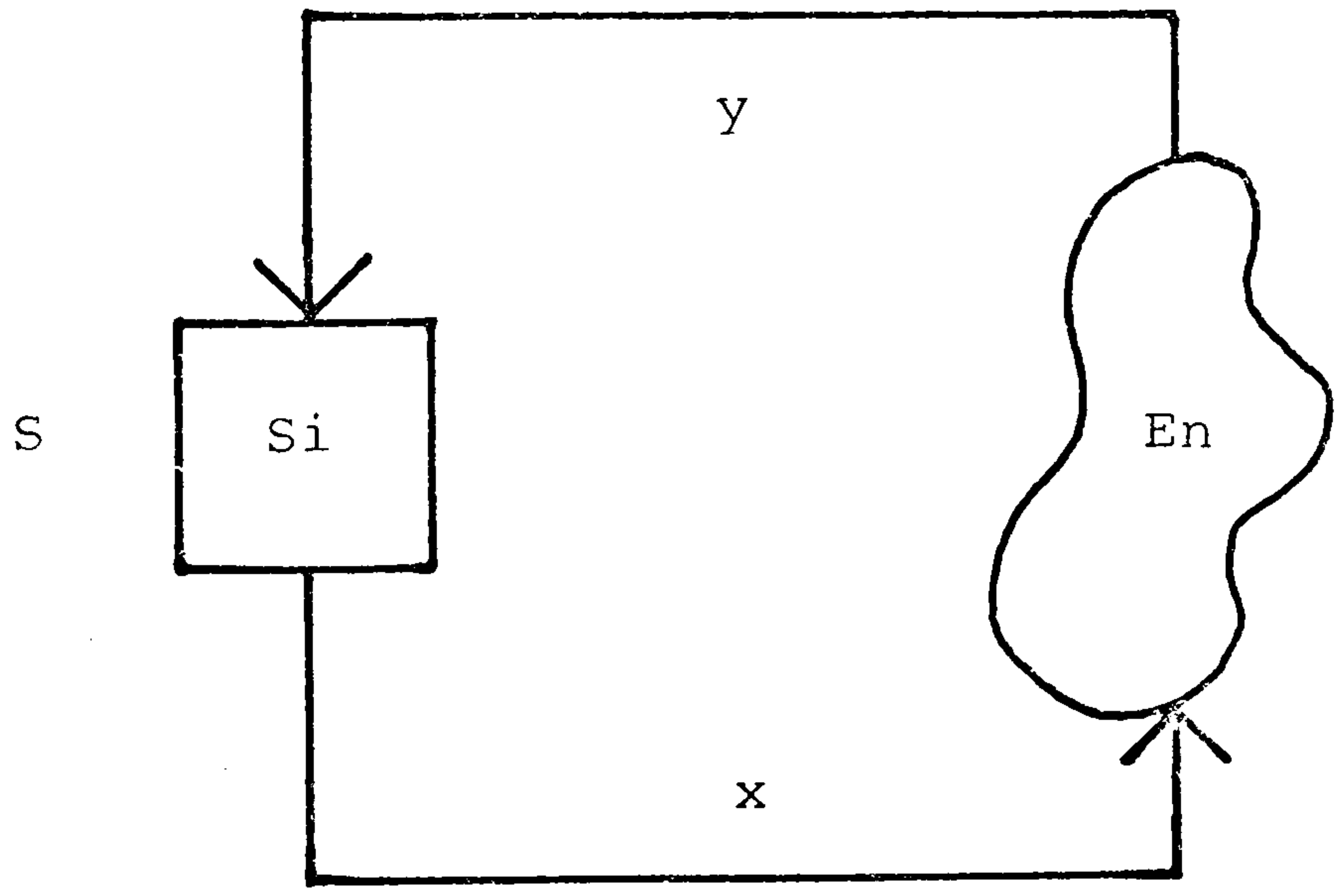

Figure D.1. A System-Environment Interaction

The problems of the system's viability, and of its effective survival, are interpreted with respect to a specific correlation existing between the value of inputs originating from the environment and the respective outputs that represent the system's response. How change in the system's output as well as in its internal states relates to maintaining such a relation stable, or even optimizes it in the face of unpredicted environmental variations, are the central questions of the theory of regulation. In this respect the dynamics of a system-environment interaction with its typical feedback characteristics provide the context in which problems of stability, adaptation and evolution are discussed.

D-2 The Machine as a Metaphor

Because of the nature of the dynamic processes that are involved, the behavior problems associated with a system-environment interaction relate very strongly to the concept of change, the problem of synchronizing change and of optimizing such a synchronization. The theoretical framework for discussing such problems and, in fact, of discussing behavior in the most general sense of the term, is provided by the concept of abstract machines and the theory of automata.

The concept of an abstract machine is due to Ashby who tried to capture with it the essence of regularity in behavior. We have already mentioned Ashby's insistence on the need for a theory which would deal with behavior in general and which would provide a comprehensive conceptual framework to which the working of actual systems could be related. His notion of a "machine" must be understood with this broad objective in mind.

While the word "machine" is commonly associated with the notion of a mechanical device that immediately brings to mind the image of a physical artifact, the concept of an abstract machine stresses the essence and nature of processes that underline the behavior of dynamic systems in so far as such behavior shows some form of regularity. The emphasis is on the processes that are inherent to various manifestations of behavior, and on problems of their description, rather than on the nature or identity of a system as a "thing." Accordingly, the interest is with the logic and "laws" relating to a succession of orderly behaviors, and not with the materiality, or functional details, of the system in question. As Minsky points out, "Our concern is with questions about the ultimate theoretical capacities and limitations of machines rather than with the practical engineering analysis of existing mechanical devices."(4)

The concept of "machine" thus centers on the problem of modeling the fundamental and most general features of behavior. This means abstracting the operation of a system to the essential structure of sequences of events that represent its activity. Such events are associated with "states," representing the unique and recognizable system conditions that undergo orderly transformations. In this way, the behavior of a system can be represented by a succession of states and the rules for their transformations. Such systems states and their transformations are described by the logic, structure and dynamics of informational processes, and, in fact, the theory of automata is embodied in various different abstract models of information processing machines. In the simplest sense, a machine of this kind can be regarded as a device that transforms some incoming messages to outgoing messages, according to a given rule of transformation. Its activity will consequently be represented by a code depicting a succession of states.(5)

The simplest type of machine is a state determined machine that is isolated in the sense that no external input affects its transformations. It is associated with a finite set of possible states and with each transformation, only one specific state of that set can occur. It is thus represented by a closed single-valued transformation in the sense of Ashby,(6) and it can model only the simplest forms of strictly determinate behavior.

A more general type, of which the first is a special case, is represented by the typical finite state machine, otherwise known as a "machine with input." In this case, it is the machine's internal states at a given time, and the states of its environment at that time, which determine the next state that it will assume. When the internal state at any time t is designated by Q(t), and similarly the environmental input and the system's response are designated by S(t) and R(t) respectively, a complete description of the machine's behavior can be obtained by two functions, say F and G, one defining the response R at time (t+1) as a function F, of the internal states and the inputs at time (t), and the other defining the internal state Q at (t+1) as a function G, of the internal states and the input at time (t). The two functions are written as follows:

$$R(t+1) = F(Q(t), S(t))$$

$$Q(t+1) = G(Q(t), S(t))$$

They provide the means for computing the system's states at any future time if the inputs are known. (7)

We have focused a brief attention on the description of a typical finite state machine, representing an archetypal machine of a great generality. The theory of automata offers, however, various other possibilities. For example, there are "Markovian" machines which are probabilistic in nature and which represent the case where behavior can be only statistically determined and is therefore given by a pair of states associated with transition probabilities. There is a particularly interesting case of finite automata--Neural Networks--that had originally been developed by McCulloch and Pitts and represents the logic inherent in discrete processes. There are Turing machines, capable not only of "reading" features of their environment (represented by a tape) and changing their own internal states accordingly, but also of modifying that environment (by altering the print on the tape). There are universal Turing machines, able to reproduce any other Turing machine, and there are self-reproducing automata in the sense of Von Newman that can reproduce a blueprint and assemble available parts to construct machines similar to, or even more complex than, themselves. There are finite function machines in the sense of von Foerster that can similarly reproduce, or selectively modify, a pattern representing their own internal states. And there are others, all representing different aspects of different problems associated with various forms and manifestations of behavior, but all sharing a basically similar logic.(8)

There are, however, various limitations involved. Some have to do with the logic of computation and with the very limits of computability.(9) Others, on the other hand, relate to various features that are inherent in the structure of the theory and restrict its usefulness in representing certain aspects of complex behavior. For example, the fact that the machine state description requires that states will be uniquely and precisely defined and the fact that machine computation is sequential, represent such difficulties.(10) But with the incorporation of concepts that are inherent in Petri nets and Holt's concurrent systems, as well as notions associated with Zadeh's theory of fuzzy algorithms, the initial repertoire can be extended. It can thus include the case of parallel computation, and hence, for example, of cooperative interaction between initially asynchtomized automata, as well as cases where states in a set are not precisely defined but must admit grades of membership. This last concept is particularly important because it allows the discussion of machines with underspecified goals and thus of evolutionary processes that are typical, for example, to cognitive and social systems.

Notwithstanding the technical details that are involved, the important point that needs to be stressed is that the concept of an abstract machine represents the basic cybernetic paradigm for a complex system and its behavior. It provides a central metaphor that on the intended level of abstraction links the discussion of various purposive systems, whether they are actual machines, biological organisms, brains or societies.

D-3 The Organizational Approach in Cybernetics

The concept of an abstract machine is particularly important because of its profound effect on the general discussion of the structure and organization of behavior.

The key notion which ultimately found its way to the treatment of the behavior of a great variety of systems had been anticipated as early as in 1936 by Turing's work on the theory of computability. It was implicit in his famous theorem which stated that any behavior which could be described in precise and unambiguous terms could be simulated by a computing machine.(11) Such a description, in other words, can act as a prescription for a given sequence of behavior. The important point is not that the computing machine will resemble in exact details the system whose behavior it attempst to realize, but, rather, that on the appropriate level of abstraction, the simulation will be isomorphic with the essence of the behavior in question, to a degree which would satisfy an unbiased observer.

This idea, that a behavior is realizable in a machine once there is an effective description of it, contains the essence of a fundamental concept, central to the "organizational approach," which ultimately connected the idea of a stream of actions, or behavior, to the notion of an execution of a program. This idea, though not explicit, is also implied in Wiener's analysis of the mechanisms involved in a system's purposive interaction with its environment. Earlier we have quoted Wiener's comment on the functional similarity between living individuals and the general class of purposive machines. Wiener described the "anatomy" of this similarity as follows: "Both of them (the individual and the machine) have sensory receptors as one stage of their cycle of operations: that is, in both of them there exists a special apparatus for collecting information from the outer world at low energy levels, and for making it available in the operation of the individual or of the machine. In both cases these external messages are not taken neat, but through the internal transforming powers of the apparatus whether it be alive or dead. The information is then turned into a new form available for the further stages of performance. In both the animal and the machine this performance is made to be effective on the outer world. In both of them, their performed action on the outer world, and not merely their intended action, is reported back to the central regulatory apparatus."(12)

According to the description given above, the operation of a purposive system depends on the integrated functioning of the following components:

1. a sensory apparatus for the detection of relevant external variations, the latter providing informational inputs and acting as activating sources;
2. an evaluation and decision element containing the appropriate transformation function by which incoming information is operated upon according to pertinent internal criteria;
3. an appropriate affector whose actions, guided by the "decision" element, are directed to the external world; and
4. a capability for monitoring such actions by feedback.

From a functional viewpoint, these components are linked operationally in what may be termed a "loop of action." Such a loop, which is typical to purposive systems in general, consists of a sensing apparatus, an evaluation and decision function, and the appropriate affectors together with the relevant informational paths and feedback loops. From an organizational viewpoint, however, the emphasis is on the goal directed structure of purposive actions, on the notion that the internal criteria for evaluating incoming information can be interpreted as a goal of the system,(13) and that such a goal must therefore contain some form of prescription by which actions are mediated.

Accordingly, the essence of the organizational approach is in seeking to model a system's behavior by the dynamic interaction of its goal-directed components. In Pask's words: "The organizational model is reducible to units associated with goal achievement or command interpretation. . . . Hence it is able to explain the working of a real system with which it is identified."(14) This identification is carried on to a level of abstraction in which the operation of functional entities is discussed in terms of programs and their execution. A program is meant in the sense of a computer program, but essentially it is regarded as "a formula for achieving a goal."(15) It provides a procedure, or a "plan," that regulates the order in which a particular sequence of actions is performed. It is not surprising, therefore, that the organizational model which discusses behavior in terms of the execution of such plans is often couched in computer programming terminology. As Miller, Galanter and Pribram remark, "The notion of a plan that guides behavior is, not entirely accidentally, quite similar to the notion of program that guides an electronic computer."(16)

D-4 Simulating the Functioning of the Reticular Formation -- An Illustration

A particularly elegant illustration which brings out the logic of the organizational approach is furnished by the work of McCulloch and his colleagues on simulating the functioning of the reticular formation. In connection with this work, McCulloch's concept of the Redundancy of Potential Command is all-important.(17)

McCulloch coined the term Redundancy of Potential Command to describe a network of "decision making" elements each of which is potentially capable of assuming command of the total net. These elements are coupled in such a way, and their interaction with their environment is such, that only one can command at any instant. Which particular element will actually be activated depends on the distribution of pertinent information in the whole network at a given time. The potential for command is thus distributed over a large number of components and the actual location of command shifts constantly within the network. There is no unique specification that identifies a particular location with a specific decision and because of this an observer is unable to pinpoint the exact location in which a decision is generated.

Because of its redundancy, such a network is self-organizing in the sense of von Foerster,(18) and the implication of its mode of functioning to the general problem of generating reliable decisions, is profound.(19) For the moment, however, we shall be particularly interested in looking at the interpretation of the concept with respect to the operation of the reticular formation.

The reticular formation of the brain is a network of neurons constituting a mechanism which mediates between a number of instinctual behaviors in a vertebrate animal. It commits the animal, at any time, to one of a few basic but incompatible modes of behavior.(20) It directs the animal's attention, and regulates the performance of its different possible activities by selecting that mode of behavior which seems most appropriate at a particular moment. The criteria for selection is furnished by available information about the animal's general physiological condition as well as by information about relevant conditions in its environment.

According to McCulloch,(21) the reticular formation can be thought of as a computer integrating signals arriving from various parts of the body and from other parts of the nervous system. In his words, the function of this computer--"given its knowledge of the state of the whole organism and of the world impingent upon it, is to decide whether the given fact is a case under one or another rule. It must decide for the whole organism whether the rule is one requiring fighting, fleeing, eating, sleeping, etc."(22)

The significant fact about the structure and functioning of the reticular formation is that it can operate effectively in mediating behavior only by virtue of its inherent redundancy of potential command. As McCulloch pointed out, "Of necessity, the system must enjoy a redundancy of potential command in which the possession of the necessary urgent information constitutes authority in that part possessing the information."(23)

On the level of abstraction which concerns us here, the working of the reticular formation can be interpreted with respect to the notion of regulating the execution of a finite set of programs which specify specific behavior sequences. In this sense, as Pask puts it, the concept of redundancy of potential command can be taken "to describe the relationship existing between a set of goal directed sub-systems which compete for dominance."(24) As programs, they compete for being executed.

Each such program is a goal directed component in a set containing the whole behavioral repretoire. Each program is associated with a specific activity that the organism may perform. Only one such program can be run at a time and the question of which one will actually be executed, which one will momentarily dominate, depends on which of these goal directed sub-systems is in possession of the most relevant information. The criteria for relevance may be generated locally, but generally it depends "upon the weight of evidence in respect to all of the modal computations and also upon the feedback from the critical processes engendered by the immediate commitment."(25) Ultimately, of course, it depends upon serving effectively the overall goal of survival.

Typical to the organizational approach, the theory seeks to explain a complex behavior, in this particular case, a behavior concerned with the problem of how regulating certain activities is achieved by a specific part of the nervous system. The explanation proceeds by identifying the regulating mechanism involved, by resolving its operation into the organization of interacting goal directed sub-components and by pointing out the rules which mediate the operations and interactions of these components within the context of the whole.

D-5 The Organizational Model

The organizational approach has proven particularly useful in the discussion of the behavior of systems where processes of social interactions and mentation are involved. The basic logic of the approach has found expression in various fields associated with the life sciences, for example, in ethnology, the social sciences, and psychology, and the fact that a similar logic underlines the discussion of a considerable variety of problems in such diverse fields, justifies the notion of an "organizational model" providing the consistent conceptual framework that is used throughout.

An extensive discussion of the organizational model is due to Pask,(26) who is also responsible for the term. The key idea is of regarding the class of systems for which the approach is relevant, essentially as general purpose computing machines and discussing behavior in terms of the various classes of programs that are run in such machines. The programs themselves are related to goal directed processes in that they are regarded as "formulas for achieving goals" in the sense previously discussed.

In this way, the representation of a variety of systems, from brains to societies, can be made in analogous terms, all abstracted on the level of discussing programs that are being executed in computing mechanisms. The emphasis on functional entities and their respective structures, that is typical to other possible approaches, is replaced with an emphasis on the content, organization and dynamics of such programs and especially on questions of how their stability is maintained, how they interact, reproduce and evolve. The central role and full extent of the preoccupation with the concept of programs is clearly emphasized in Pask's definition of the organizational model which states that "Organizational models prescribe and describe algorithmic processes, including processes that interpret statements about norms or regulations and processes that construct norms and issue instructions."(27)

Implicit in the definition is a language from which the program processed by a system is constructed. The specific "programming" language used is the "object language" with which a given system is identified and by which it "communicates." It is quite distinct from an observer's meta language by which the actual process of communication is described. The system itself is a "language oriented system,"(28) in the sense that it can use its object language to interact with other systems of a similar kind. In the typical case, a statement in the object language, acting as an input to a recipient system, is interpreted by that system's evaluation and decision function, its "brain" perhaps, with the result that according to relevant internal criteria an appropriate program is selected for execution and a particular process is set in motion. This, of course, looks immediately useful in the discussion of instinctual behavior, but the central idea can be extended to cover other and more complex forms of behavior.

The object language itself can assume a great variety of forms. It can be associated with any system of codes, signs or stimuli, organized in a chemical, audio, visual or other domains. It can be a conventional natural language, a scientific or a computer language, and it can also be embodied in the rich diversity of subtle gestures and symbols which have meaning in the context of a culture.

The relevant criteria is that the language is recognizable by a recipient system, that it is interpretable by it, and that it conveys a meaning to it. In this sense, incidentally, the idea of an input obtains an important qualification in that to be effective an input has to belong to a class of statements that is recognizable by a particular processor.(29)

An important consequence that is inherent to the logic of the organizational model is a somewhat uncommon view of what constitutes the "individuality" of a system. As Pask points out,(30) the identification of a system with a functional and usually physical entity is replaced with an emphasis on the concept of organization. More specifically, on the concept of a particular class of programs bearing a specific name. To be sure, the programs are executed in a real processor, but the actual line of demarcation is defined by the pertinent range and boundaries of informational processes and it may shift according to an observer's special interests. It may thus be associated with a single system or with a few systems interacting communally.

In summary, the organizational model provides a conceptual tool for analyzing the behavior of systems where such behavior is abstracted to a level at which it is represented by the dynamics of informational transactions. In so far as such systems are associated with social or cognitive-like processes, they are regarded as "language oriented" systems, and their behavior is identified with specific classes of programs, being executed in complex organizations of interacting goal directed components. Due to the generality of the concepts underlying the approach, various aspects of the organizational model have found expression in widely different fields. Some typical examples illustrating the usefulness of the approach in a few selected disciplines will be cited below.

D-6 The Structure and Organization of Behavior

In behavioral psychology, the approach has been lucidly articulated by Miller, Galanter and Pribram in their book Plans and the Structure of Behavior.(31)

In developing their argument, these authors stress the inability of the classical behavioral model, based on the idea of a stimulus-response sequence, to explain any but the simplest forms of behavior. They also point out that attempts to extend the classical model by introducing the notion of an organism's image of its environment,(32) is not sufficient for a comprehensive explanation of complex patterns of behavior. An internal representation of the world, they feel, cannot, in itself, account for the dynamic activity which characterizes an organism's interaction with its surroundings, and this model, too, is lacking. Nevertheless, they regard elements of the classical model, as well as the basic notion of an image as fundamentally useful, and they seek to retain the essence of both. Their theory attempts to generalize the idea of the reflex arch in a way which would enrich the behavioral model, provide a comprehensive explanation for various observable behaviors, and, above all, bridge the gap between cognition and action.

In order to bridge this gap and link the idea of an organism's image of the world with its behavior, Miller, Galanter and Pribram introduce the concept of a plan that is regarded as the principle which guides behavior. Their "Plan" is essentially conceived of as a set of instructions, and noting the fact that, typically, behavior is hierarchically organized on several levels of complexity, they see such a Plan as "any hierarchical process in the organism that can control the order in which a sequence of operations is to be performed."(33) In so far as a Plan stands for a set of hierarchically organized instructions which mediate a sequence of actions, it fulfills a similar role to a program in a computer and, indeed, throughout the discussion both terms, a plan and a program, are interchangeable.

In their model, the authors combine the idea of an Image with the notion of a Plan to form a basic unit of analysis, a simple building block, with the orderly compounds of which complex behaviors can be described. This basic building block is their TOTE unit (for Test-Operate-Test-Exit) which is essentially a generalization of the concept of the reflex action, the alternative they offer to the reflex arch. It is described in the following words: "The general pattern of reflex action . . . is to test the input energies against some criteria established in the organism, to respond if the result of the test is to show an incongruity, and to continue to respond until the incongruity vanishes, at which time the reflex is terminated. Thus there is a feedback from the result of the action to the testing phase, and we are confronted by a recursive loop."(34)

The idea of the reflex action is embodied in the structure of the TOTE unit, and it echoes the fundamental cybernetic contention which identifies the basic building block of the nervous system with a typical feedback loop. The concept stresses the hypothesis that various aspects of behavior are guided by the results of pertinent tests, and consequently the diagrammatic representation of a TOTE unit is as follows:

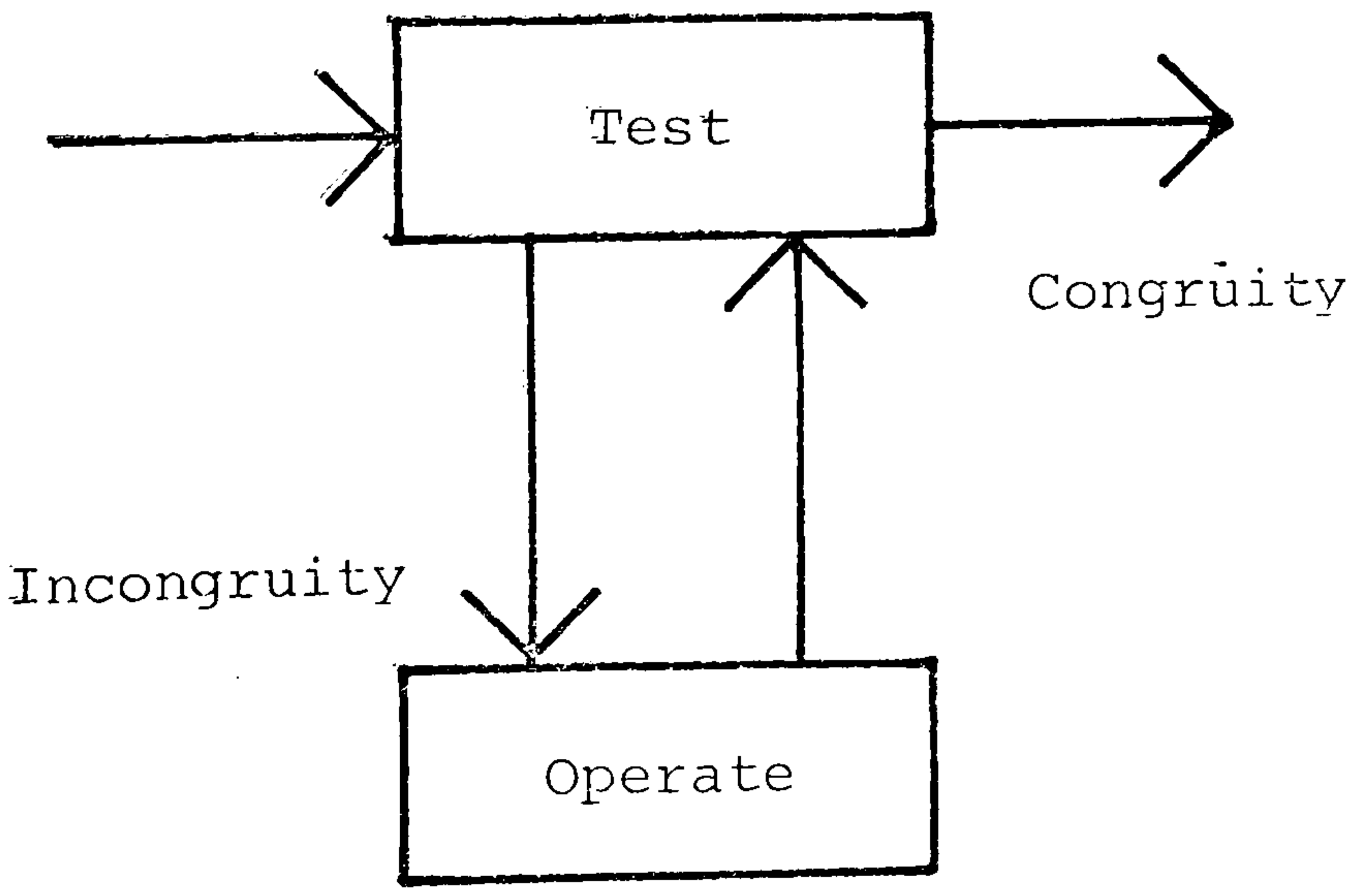

Figure D.2. The TOTE Unit (From Miller, Galanter and Pribram)

Emphasizing the essentially cybernetic characteristics of the TOTE unit, the authors propose that it could offer an effective model not only for the simple reflex but for behavior in general. This by virtue of two fundamental contentions that are central to the theory: firstly, the TOTE unit can be interpreted on various levels of abstraction. On one level, it may represent energy flows and thus be identified with the physical anatomy of processes involving, for example, the operation of a neuron or the simple reflex. On another level, however, it can be identified with flows of information and consequently with control processes and it can thus be associated with higher and more complex forms of behavior involving decision making, problem solving, and the like.

Secondly, TOTE units can be combined into hierarchies representing the integration of many plans in structures of arbitrary complexity, and such hierarchies can be identified with the performance of a continuous stream of specific actions depicting complex patterns of behavior.

The effectiveness of such TOTE hierarchies in modeling behavior is enhanced by the fact that a complex hierarchy of TOTE units preserves the fundamental characteristics of a single unit, in that "the operational phase of a higher order TOTE might itself consist of a string of other TOTE units, and each of these, in turn, may contain still other strings of TOTEs, and so on."(35) Similarly: "the 'objects' that this coordinating TOTE hierarchy test and operate upon, are themselves TOTE hierarchies."(36)

As is typical to descriptive problems associated with complex hierarchical organizations,(37) each given level in such a TOTE hierarchy is describable only by the next higher level. A TOTE hierarchy may thus represent a hierarchy of descriptions, or languages, that are organized in successive levels in which each higher level provides the metalanguage by which the content of a lower level is integrated and by which it can be discussed.

From the level of abstraction which regards the TOTE as a hierarchy of descriptions, the step is small to viewing it as an hierarchical organization symbolizing control processes. From an operational viewpoint, arrows could thus indicate the order of subordination of some processes to others and the whole hierarchy of arrows stringing units together would specify the succession of execution of Plans and consequently the sequence and conditions for transfer of control.

A TOTE hierarchy can be interpreted therefore as describing processes of regulation. In behavioral terms it describes the regulation and execution of a string of actions with which a particular behavior is identified. The performance of such actions is directly related to the execution of specific plans and in theory, no matter how complex a sequence of actions actually is, it could be described by a properly constructed assembly of TOTE hierarchies. The problem of constructing such an assembly is in identifying the relevant single TOTE units, the rules for their interaction, and the logic of sequencing their operations.

The TOTE unit thus offers a concept of considerable generality with which useful organizational models of behavior can be constructed and their structure analyzed. In addition to instinctual behavior, Miller, Galanter and Pribram discuss their behavioral model with respect to various motor skills and habits, problem of memory, and of speech, and they touch upon the problem of learning viewed in the sense of the modification of existing plans and the formation of new ones. A particularly interesting interpretation of the model is developed in relation to speech, where the authors draw attention to the hierarchical organization inherent in most languages, especially in the structure of grammar. They raise the general problem associated with the relation between languages, thought processes and behavior,(38) and they conclude with the suggestion that "We might speak metaphorically of a general grammar of behavior, meaning that the grammar of language was only one example of a general pattern of control that could be exemplified in many other realms of behavior."(39)

D-7 Examples from Biology and Ethology

The general characteristics of the argument are implicit in various biological studies and they are illustrated particularly clearly in the field of ethology where a great deal of animal behavior can be interpreted along the lines discussed above.

From the "organizational" viewpoing, biological organisms can be regarded as computing mechanisms that are adapted for functioning in particular environments. Their adaptation is manifest in the development of a particular set of programs that are characteristic of a given specie and on the automatic execution of which, the survival and well-being of the organism depends. The development of such programs is the selective consequence of a long adaptive interaction with an environment, and their content and operation can be interpreted on various different levels. For example, such programs may relate to internal physiological functions, they may have to do with the behavior of an individual organism, or they may be associated with the overall behavioral patterns of an entire specie. For each such level of resolution an environment can be defined which is the source of variations impinging on the system in view. Some of these environmental variations provide the stimuli which trigger the specific sequence of events in the organism and others give rise to various manifestations of behavior directed back at the external world.

Problems of development in biology, for example, are discussed by Waddington(40) and Bonner(41) in terms which clearly bear the prints of cybernetic terminology. Bonner speaks of development as of a control process in which events occur sequentially and in which specific molecular interactions continuously create conditions that trigger the control action of specific genes, thereby creating new circumstances stimulating yet other events and so forth.(42) Elsewhere,(43) Bonner refers to the development of a single cell into a multicellular organism, as to an hierarchical control process requiring several levels of descriptions. Moreover, he finds it useful to introduce the concept of developmental tests in order to account for particular lines of development. According to this concept, a cell in a developing organism performs various tests on its environment and "it is on the basis of the results of such tests that the appropriate genes are turned on to conduct the appropriate developmental processes."(44) A hierarchy of control which is associated with several levels of descriptions is therefore needed, in order to regulate the various successive phases of development.

While molecular control mechanisms, which mediate developmental processes and operate on the level of chemical interactions, may be discussed in terms of "communication" between goal directed sub-systems in the organism, they do not require the use of the concept of "language oriented" systems in its full blooded snese. The concept is essential however for the discussion of various traits of animal behavior, and, in general, contemporary ethology illustrates quite distinctively the logic of the organizational approach.

Von Holst and Mittelstaedt, for example, (45) studied problems associated with an insect's internal control of sensory stimuli and its relation to motor response. They have explained certain behaviors, in which correction of movement follows visual stimuli, by invoking the concept of a "template," existing "in" the organism, and containing a representation of what a particular re-afferent stimulus "should be." The difference between the internal representation of the "expected" and the actual stimuli dictates the response which follows. Similarly, much of animal behavior is described in terms quite like those associated with the notion of execution of plans in the sense of Miller, Galanter and Pribram. The general view is that such programs are "turned on" by specific stimuli which may originate from an environmental change or which may be associated with a specific pattern of behavior performed by another member of the species.

A typical example is furnished by seasonal changes that trigger a specific action or a sequence of behavior. A change in the length of day, for example, provides the environmental stimuli on which the initiation of reproductive behavior in certain animals depends. As Tinbergen has shown,(46) such a behavior is composed of a complex sequence of different actions which, once triggered by a particular environmental condition, follow sequentially in an orderly and rigidly prescribed manner. Dubos describes such behavior as follows: "In many animal species, the chemical changes in the sex glands that occur as a response to the environmental changes associated with spring, initiate the process of courting and display. In birds, for example, this process is followed by nest building, which begins at a proper time, with the choice of the right material. Mating and egglaying follow, then breeding and the feeding of the young."(47)

The release of a typical pattern of behavior by a particular stimulus is associated with the concept of an organism's "innate releasing mechanism," attributed to Konrad Lorenz. The concept refers to the automatic, inflexible execution of prescribed plans, the content of which is a result of the long experience of a whole specie, transferred genetically, and which individual animals do not have to relearn with each generation. Of necessity, behaviors associated with such a fully prescribed pattern must be well integrated with a particular environment in a total ecological sense. They are the outcome of millenia of evolutionary adaptation.

Many instances of inter-specie behavior can be given a similar interpretation. In such cases, the stimulus is provided by a member of a specie performing an act which receives a specific interpretation and elicits a specific response. Courting sequence and love play of many animals follow a ritualistic performance, the component acts of which clearly convey a meaningful message and trigger specific reactions. Lorenz's description of fighting behavior in the fighting fish spells this out very clearly: "When two males meet face to face, veritable orgies of mutual self-glorification take place. There is a striking similarity between the war dance of these fish and the corresponding ceremonial dances of Javanese and other Indonesian peoples. In both man and fish the minutest detail of every movement is laid down by immutable and ancient laws, the slightest gesture has its own deeply symbolic meaning."(48)

Very similar in principle are the intricate dances performed by bees as a means of communicating the location of flowers to other members of the hive. In automatic response to a performance of such an instinctive dance, groups of worker bees will rush out of the hive and fly towards the indicated source of food.(49) Rituals of self-excitation, performed by packs of wild African dogs as they prepare for a hunt, offer another typical illustration of the same principle, and there are many more examples. Humans, too, show various biologically conditioned, instinctive behavioral traits. For example, Oswald and Pelzman who studied infants crying, make the following comment: "The sound stimulates strong feelings and distinct reactions from almost everyone within earshot. Undoubtedly, much of the effect of the infant's cry is biologically determined in order to guarantee that the infant receives care and nutrition."(50)

In summary, both individual and social instinctual behavior in animals can be readily interpreted by the organizational model. In both cases, particular patterns of behavior are associated with pre-programmed plans of varying degrees of complexity. The execution of such plans, and consequently of a particular sequence of behavior, depends on the interpretation of, and a reaction to, specific "releaser" signals.

D-8 Extending the Organizational Model to Problems of Cognition and Learning

The possibility of extending the organizational model to problems concerning cognition and learning is particularly significant since demonstrating the cogency of the model with respect to these areas would enrich its scope considerably. Such an extension would allow the discussion of higher forms of behavior, notably where cognition, consciousness and evolutionary processes are involved, thus vesting the simple model consisting of TOTE hierarchies with a greatly enhanced generality. In this respect, an important contribution is due to Pask's theory of cognitive systems and learning processes.(51)

Pask has stressed the fundamentally purposive character of cognitive systems.(52) The essential point is that cognition in general and intelligence in particular are relative concepts which require the notion of a specific goal in relation to which they obtain their meaning. A system is said to show evidence of intelligence when its behavior is interpretable as being effective with respect to a particular goal that it seeks to achieve. Similarly, various processes which are associated with cognition can be regarded essentially as processes involving problem solving, where the notion of problem solving is related to the effective utilization of available information in an attempt to bring about a particular goal. Because a "problem solver" can be regarded as a controller that operates on a particular environment in order to bring about a specific outcome, the idea of a cognitive system can be represented by a typical goal-directed unit that is isomorphic with a simple TOTE.

Such isomorphism exists because the TOTE unit itself is a goal directed system in which the test phase is associated with a specific goal. The unit is activated by a command to achieve such a goal and the Operation phase represents a continuous approximation to attaining that goal. Following the Test phase which checks for congruency, an Exit phase signifies the achievement of the goal and consequently the transfer of "computation" to other units. Emphasizing its "control" aspects, the generalized diagrammatic representation of such a basic goal directed unit takes according to Pask the following form:

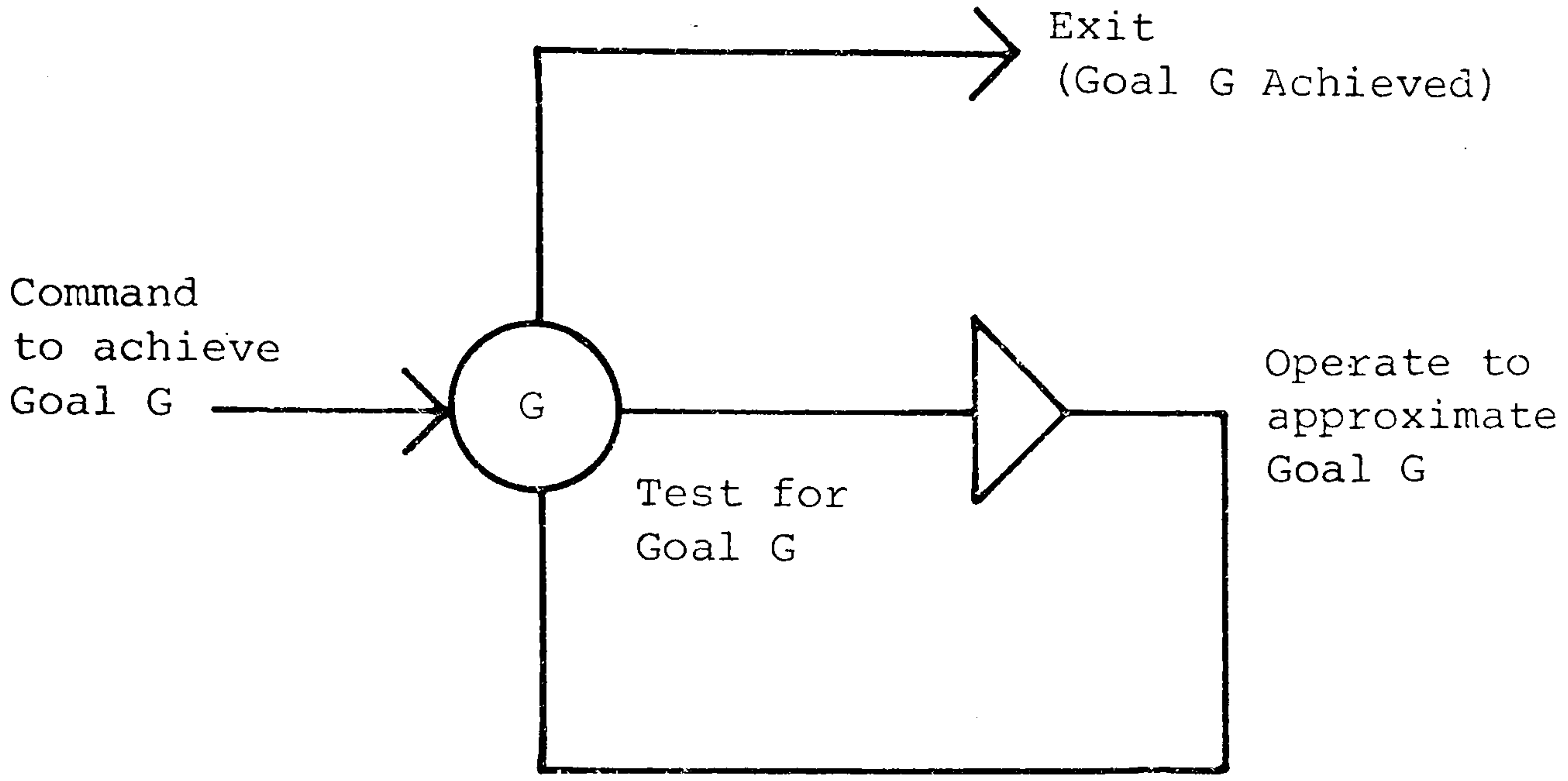

Figure D.3. Goal Directed Tote, or Control Unit (from Pask).

The simple control unit of Figure D-3 offers the basic paradigm for a generalized cognitive system, and a number of such simple units can be combined in structures of arbitrary complexity to represent various aspects of behavior involving mentation. Such structures are isomorphic with the TOTE organizations of Section D-6. Thus, for example, basic goal directed units can be joined together in sequential strings, or they can be organized in complex hierarchies where there is a distinction between goals and sub-goals according to the various levels in the hierarchy.(53) In either case, the entire structure, consisting of goal directed components, is goal directed itself. For example,

Figure D-4 below represents a two-level hierarchy where:

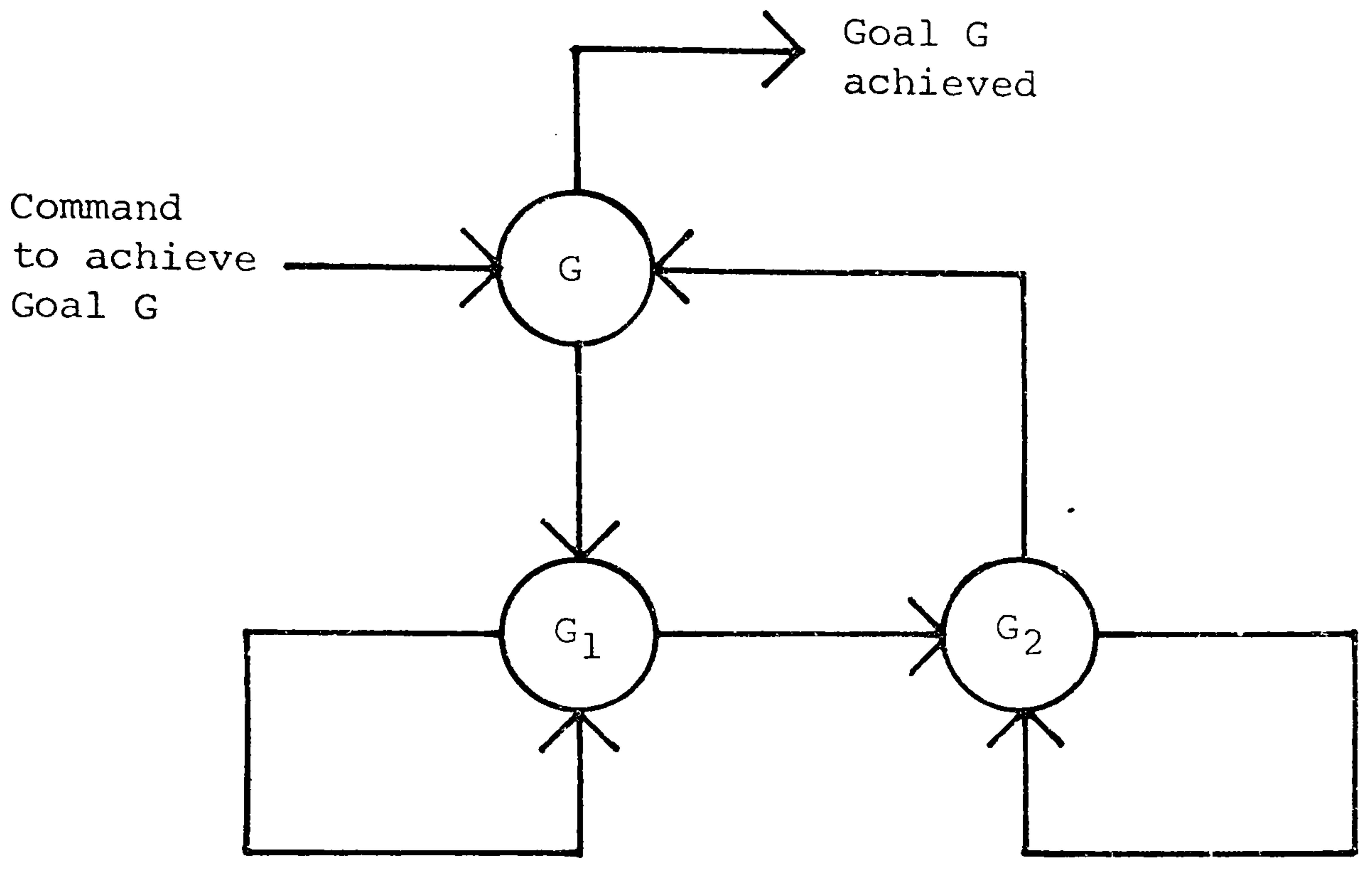

Figure D.4. A Hierarchy of Goal Directed Units
(after Pask)

"The entire system has a goal G, and subgoals G_1 and G_2. In order to attain G, the uppermost unit calls for the execution of a G_1 subroutine and a G_2 subroutine, such a predictive sequence being a Plan."(54)

The behavioral repertoire that can be modeled by organized hierarchies of the goal directed units discussed above is greatly enhanced because, as Pask points out, the basic unit employed can receive quite a few interpretations. We have already seen that a fundamental isomorphism exists between the typical goal directed unit and a TOTE, and that this unit may also be used to represent a cognitive system, a problem solver, and a control procedure. In addition,(55) it can represent a concept, where the latter is interpreted as a procedure for "knowing" or recognizing certain patterns in an environment, and it can also be identified with a game player, and thus be related to various aspects of co-operative or competitive behavior which may develop as a result of goal seeking activity in a population of interacting goal directed systems.

The notion of a complex TOTE hierarchy representing cognitive processes and especially the idea that such a purposive organization consists of goal directed sub-components which may interact in various ways, cooperating or competing, as the case may be, in the process of seeking their goals, involves a structural and behavioral dynamism which implies ultrastability in the sense of Ashby.(56) It is immediately reminiscent of McCulloch's networks possessing a redundancy of potential command, and it can be shown to possess self-organizing properties in the specific sense of von Foerster. It can therefore be quite useful in representing various aspects of evolutionary processes, especially if we allow for the possibility of parallel in additicn to strictly sequential computations. As Pask argues, however, a few more refinements are needed if the simple cybernetic paradigm involving the basic building block of the organizational model is to prove satisfactory in the realm of problems associated with learning, evolution and conscious experience.

Firstly, the idea of a goal itself requires a further elaboration.(57) Basically, a fundamental distinction is made between two types of goal, a specified goal and an underspecified goal. The one represents the idea of a clearly laid down algorithm, the other a general heuristic. The one, "normal," is a precisely prescribed procedure for the attainment of a specific goal; the other, "evolutionary," resembles a general guideline, or a general optimization principle, directed towards an open-ended objective. The basic cybernetic notion of purpose which has been identified with the specificity and well defined goal of a simple feedback scheme is thus considerably extended by admitting the ambiguity and fuzziness of an underspecified goal. The former would represent the case of a straightforward servomechanism, whereas the latter is typical to systems that evolve. It is characteristic of living organisms, for example, that "Whilst each of the goal-directed subsystems has a fully specified goal (for example, 'mediate eating behavior'), the goal of the system as a whole is underspecified ('general stability' or 'survival' or something of that sort)."(58)

Next comes the issue that systems described by the organizational model, especially those associated with social behavior and psychology, are language oriented systems in the sense of Section D-5.(59) The crux of the matter is that as such a system interacts with other similar systems by using its object language for communication, it can describe its current state or accept instructions, some of which may result in modifying, or adding to, its already available repertoire of programs. Depending on circumstances, the process can thus be interpreted in the context of adaptive interactions that are typical to some forms of learning.

Finally there is the important contention that in the context of cognitive processes the basic goal directed system of Figure D-3 can be expected to include such properties as the ability to interpret, to intend, and to anticipate.(60) It interprets conditions of its environment as well as messages directed to it in the appropriate object language. It can be said to intend in the sense of containing descriptions of classes of attributes that are relevant to its existence, and it can anticipate in the sense of containing instructions for carrying out a given procedure, if certain conditions are registered. The implications to theories of the psychology of behavior, and particularly to a view of man, are significant. For example, in contrast to classical behaviorism, Pask suggests that "a human being does not so much respond to stimuli as interpret certain states of his environment as posing problems, which he makes an attempt to solve."(61) Although the point is stressed in the context of psychology, where it is particularly important with regard to problems of learning, the very same notions are essential to any theory that attempts a comprehensive description of the dynamic behavior of social systems.

D-9 The Organization of Cognitive Systems and Learning Processes

A thorough review of Pask's theory of cognition and of his work on a theory of learning must remain outside the scope of the present discussion. The basic ideas involved, and especially the simple graphical notations that are used to represent the learning process, are important, however, and they will be discussed briefly below. They provide a potent cybernetic model, the logical connotations of which reflect the structure and dynamics of regulatory processes in a way which is particularly relevant to the generalized problems of reproduction and evolution. The model represents a particular form of organization that is reducible to control units, and while it is constructed and interpreted in the specific context of cognitive systems and learning processes, it is quite general in nature. The point is that on the level of abstraction that is associated with the logic of control, it is quite possible to "set a correspondence between the appearance and even the nature of conscious experience and the operations which go on in an evolutionary process."(62) Moreover, this correspondence can be effectively transported to the domain of social systems where a great deal of control is manifest in various symbolic regulatory processes which can be interpreted in similar terms.

As we have seen in the previous section, the approach is based upon the fundamental contention that "cognitive systems are certain sort of problem solving or control systems; [and] the contention that knowing entails aiming for a goal."(63) In addition there is the basic notion that systems that learn are essentially language oriented systems, and as such, they are modeled on a level which is identified with the framework of a particular object language. In so far as such systems are language oriented, they "can be asked or instructed to adopt goals by anyone who knows the object language and they may state and describe their own goal."(64) Accordingly, the learning process can be interpreted as a "conversational transaction" that takes place between a system and its environment or between a student and a teacher. Especially in the context of human psychology, Pask points out, the notion of a conversational transaction replaces the simpler model of stimulus and response. Such a conversation is a self-organizing process, during the course of which well defined concepts can be "transferred" and new concepts may evolve.

Concepts are regarded as goal directed procedures that are represented by the typical TOTE of Figure D-3. In other words, concepts are identified with a controller in so far as the latter is able to construct descriptions of various features of its environment that are then compared for congruity with a specific goal. Otherwise, a concept can be related to the idea of a procedure constituting a prescription, or a plan, by which the operations of a controller are guided. Because of the identification of "concepts" with the notions of control and problem solving, the dynamic "behavior" of cognitive systems, especially when viewed in the context of learning, can be represented by organizations of TOTE units, such as in Figure D-4, for example. These TOTE units operate upon one another in a process which reproduces, modifies, or builds up new units of a similar kind. The process of learning itself is embodied in a hierarchy of such interacting "problem solvers" and it is therefore modelable by an organization of adaptive controllers. (65)

A typical control hierarchy of this sort is represented by Figure D-5 which constitutes, in fact, a finite

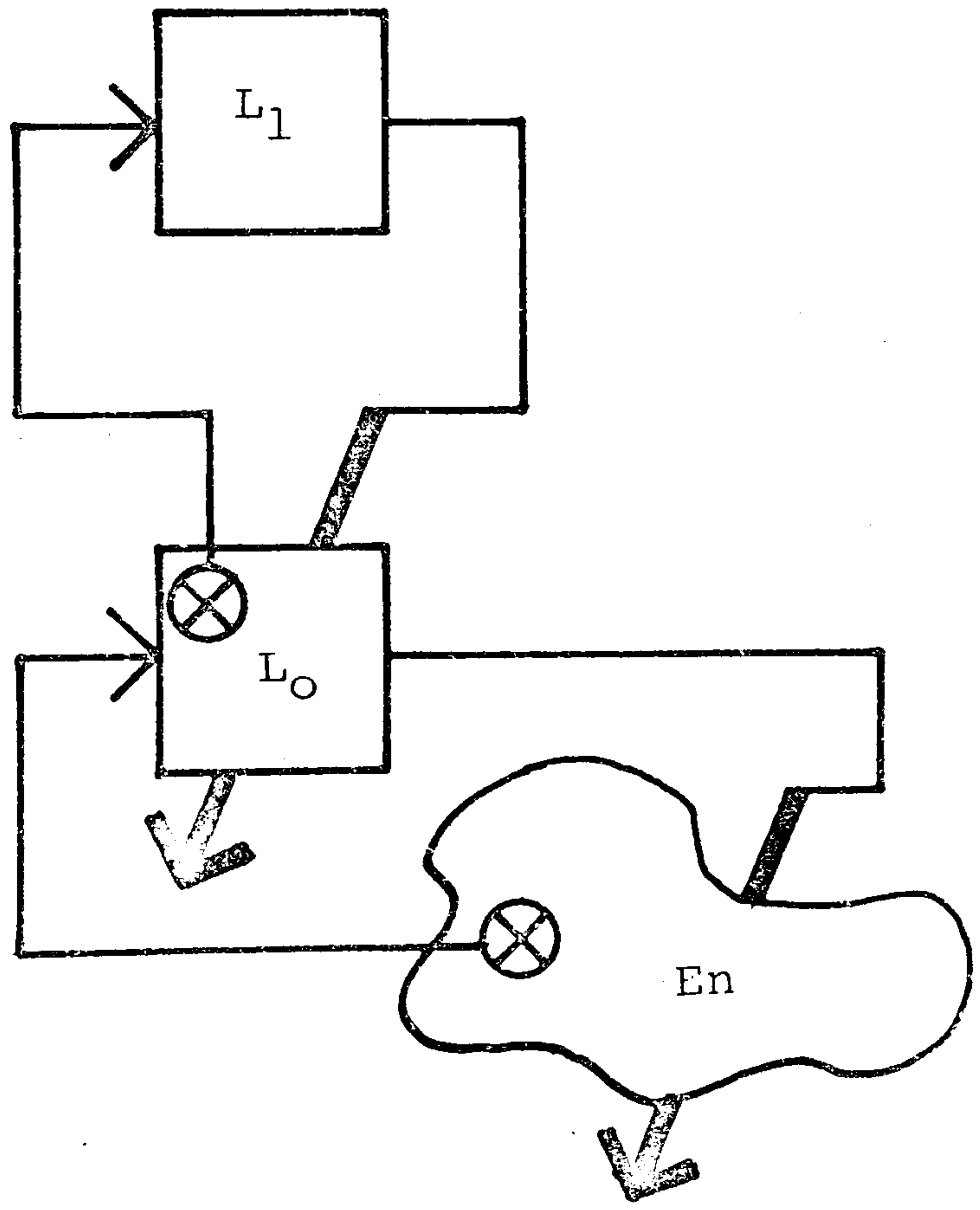

Figure D.5. A Typical Control Hierarchy (after Pask) function machine in the sense of von Foerster.(66) In this diagram the boxes labeled L_o and L_1 contain an organization of TOTE units which may take various forms and various magnitudes of complexity. The crucial point is that L_o and L_1 represent different levels, or different domains of control. The additional symbols are an arrow penetrating a box and a crossed circle. The former represents parametric operations upon the internal states of a box, while the latter represents a comparator in which a description of those states which are operated upon is compared with a given standard, to obtain a measure of deviation.

Essentially, the L_o control system senses the properties of various relevant states in an environment and it may operate to alter them. The L_1 control system, on the other hand, senses the properties of, and operates upon the L_o controllers. In the context of cognitive systems, level L_o may represent an initial repertoire of concepts, regarded as programs, whereas level L_1 represents higher level programs which operate upon L_o programs in various ways.(67) It may, for example, reproduce them and maintain a homeostatic steady state or it may operate to select among variations in L_o programs, in a process that is identifiable with some types of learning and with evolutionary processes in general. To represent evolutionary processes in the general sense, there must be an additional, higher level feedback from the environment (as shown in Figure D-6 below), which

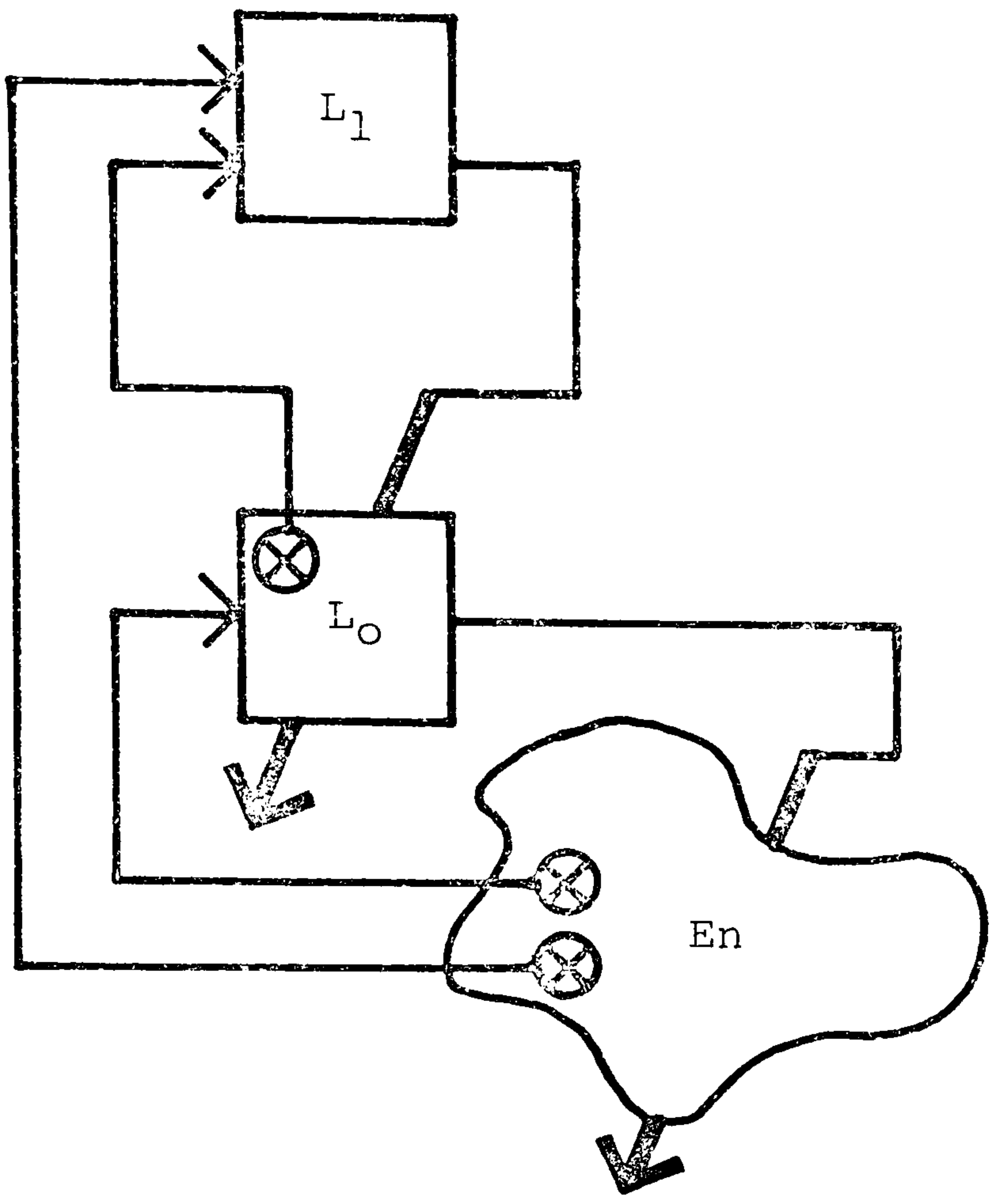

Figure D.6. The Embodiment of an Evolutionary Process in a Control Hierarchy (after Pask)

corresponds to the operations of level L_1 and which provides a reinforcing signal essential to the "guiding" operation of L_1 controllers upon the L_o domain.(68)

Learning can thus be regarded as an evolutionary process that occurs in a symbolic domain in which programs are being modified, or written afresh, subject to the guidance and monitoring action of a mediating higher level control. While the tendency will be to selectively reproduce those programs that are particularly successful in attaining relevant goals, there may be changes in the criteria of success due to significant transformations in states of the environment, for example, which will encourage a strategy of modifying existing programs or constructing new ones.

In the most general sense of biological evolution, it is the environment which poses the problems of survival and provides the criteria, as well as measure of success, constituting the guiding signal, an "algedonic" loop in the sense of Beer.(69) In the more restricted case of a typical human learning situation, the evolutionary process is mediated in the framework of a restricted domain (of certain concepts, or a subject matter) by an adaptive teaching machine or a human tutor. Here, it is the task of the mechanical or human tutor to regulate the learning activity, during the course of which goals are being set up and appropriate programs constructed in a process of conversational interaction.

The simplest paradigm for such a learning interaction is, therefore, a communication process that is embodied in the structure of Figure D-7. The communication in this case takes place in a stratified object language with levels L_o and L_1.(70) In a typical situation L_o corresponds to sequences of stimuli and responses, in the sense of problems that are posed by a "teacher" and the solutions offered by the "student." Level L_1, by contrast, is reserved for a higher level of interaction in which knowledge of results indicates a measure of success. The whole process is bound by a "mutual agreement" which specifies the rules that are pertinent to the domain of problems involved and the solutions that are deemed appropriate.

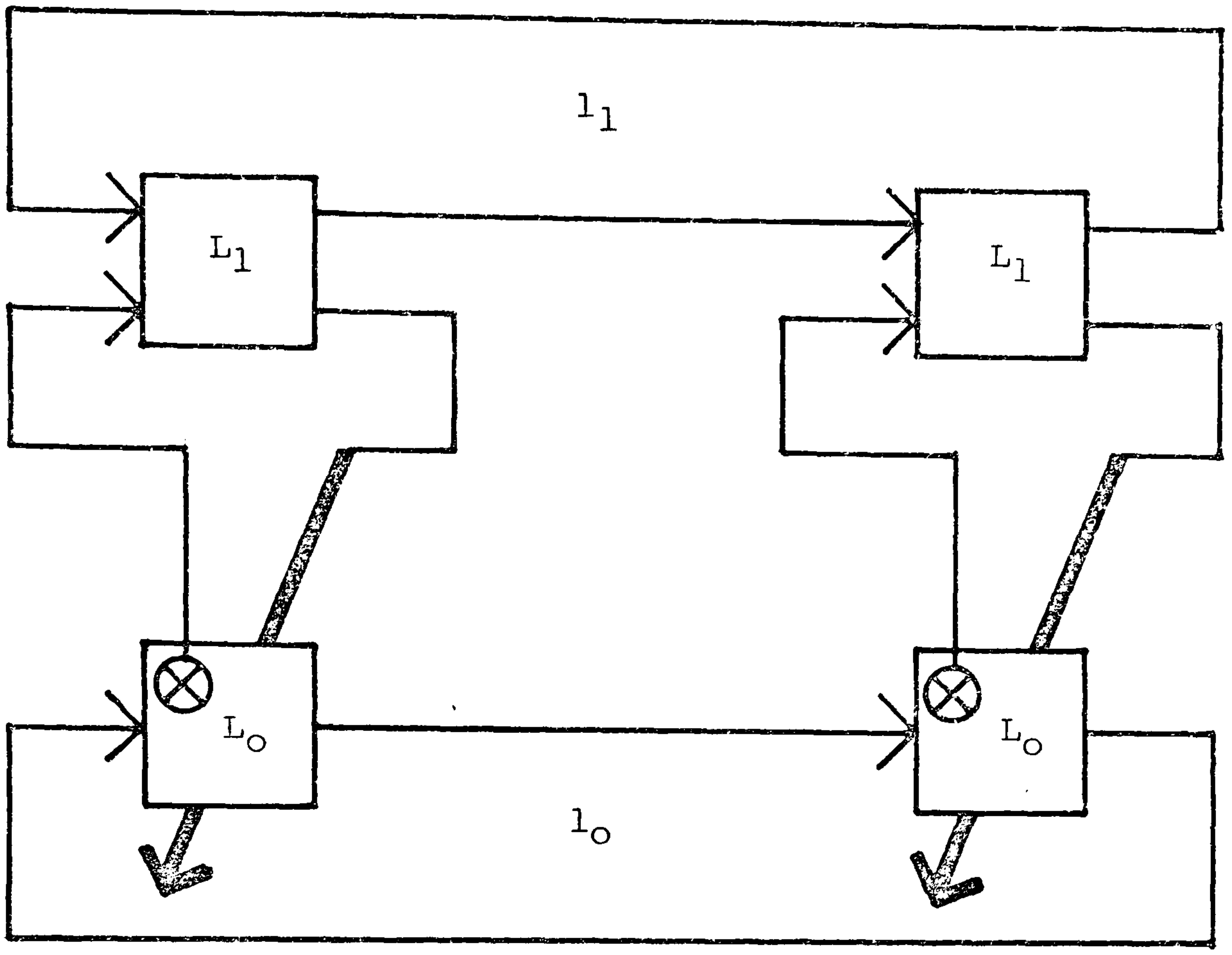

Figure D.7. The Structure of Communication Between Adaptive Controllers (From Pask)

The basic principles discussed above have been embodied in a variety of adaptive teaching systems and these have been described in a large number of publications.(71) From the viewpoint which concerns us here, the key notion that merits stressing again is that the principles by which learning and evolution are discussed relate to the operational logic of regulatory processes. These principles contribute not only to a better understanding of problems associated with learning behavior of individuals, but they are also critical to the understanding of the various social processes, upon the stability of which the social "well being" depends. The point is that on the level of social systems, human in particular, evolution occurs mainly through "externalized" learning, namely, through the selective modification of processes that are chiefly symbolic in nature.

D-10 Relevance to the Study of Social Systems

Among the various models used in the social and behavioral sciences,(72) the organizational model offers a particularly useful paradigm. From the outset, the model is developed in behavioral terms abstracted to a level which makes it suitable for the discussion of social processes. It addresses itself to the structure and modes of organization that underly behavior, emphasizing their regulatory characteristics, and providing the concepts and language which are essential for the description of viable purposive organizations. As it is reducible to units associated with regulation, the model is capable of explaining the actual working of the social processes with which it is identified, and it can thus help articulate the principles which underly the creative self-organization inherent to social systems, in both their strictly societal and total ecological sense.

That the conceptual framework underlying the organizational model has been proven effective in dealing with cognition and learning is particularly significant with regard to its applicability to the domain of social systems. As Pask suggests: "There appears to be an isomorphism between the algorithmic entity 'cognitive structure' . . . and the conventions, traditions and role structure that characterize a society."(73) Due to this isomorphism, the model provides a suitable terminology, not only for the discussion of conditions of steady state regulation that are typical to well-adapted societies, but also for the discussion of problems associated with social evolution and social change.

The approach depends on the idea of identifying social processes with specific classes of programs, on the execution of which the achievement and maintenance of various social goals depend. In this respect, two notions are crucial. Firstly, that social homeostasis is maintained by automatic mechanisms associated with traditions, conventions, rituals and so forth, all of which interact to maintain an established and proven order operative. Secondly, that social evolution can be attributed to inherent self-organizing properties that are manifest in the system's response to change. They are manifest in the appropriate reorganization of social structures and in the modification of social behavior, which may occur as a result of conceptual and technological innovations induced by the system "internally," or as a result of fundamental changes in the system's relations to its environment. In either case, the processes involved can be discussed on a level of abstraction where the operation of symbolic regulatory programs receive a societal interpretation.

Taking the particular approach offered by the organizational model, the behavior of a social system would be associated with a particular organization integrating the specific goal-directed components with which the system's activity is identified. Such "components" would be embodied in hierarchies of TOTE units, or Pask's units of control, and they would be modelable by the interaction of the appropriate classes of programs representing the processes under consideration. A specific behavior would thus relate to a specific organization of such goal directed components, namely, it would reflect the specific manner in which they interact, the structure of hierarchies and modes of control that are employed, and the particular character and content of programs that represent pertinent processes.

The stability of the system approached as an integrated whole entity, itself goal directed though in an underspecified and open-ended way, would assume typical homeostatic or evolutionary characteristics according to the nature of the general conditions underlying its existence. Its viability as a system would depend on its successful adaptation to varying circumstances. This end, of maintaining a continuous viability, would provide the overall, albeit fuzzy, goal to which all the processes represented by the appropriate classes of programs, operating singly and in their combined synergetic interaction, would be directed.

The idea of substituting classes of programs for various features of behavior implies a theory about the conditions that generate that behavior. In so far as the organizational model represents such a theory, it may help identify organizational conditions which underlie various social pathologies and it may provide guiding principles for the preventive management of such pathologies. This potential contribution is particularly significant at a time when various manifestations of social behavior are showing signs of stress and growing instabilities.

NOTES TO APPENDIX D

THE ORGANIZATION OF BEHAVIOR

1. Ashby, W. R., An Introduction to Cybernetics.

2. This is the basic notion behind the argument developed by both Ashby and Sommerhoff. See for example Ashby, W. R., "Principles of Self-Organizing Systems" in Principles of Self-Organization, von Foerster and Zopf (eds.), pp. 255-278.

3. See Appendix C, Section C-9.

4. Minsky, M. Computation, Finite and Infinite Machines, p. 2.

5. Ashby, W. R., An Introduction to Cybernetics.

6. Ibid., see particularly Chapter 3.

7. These equations represent the essence of the argument vis a finite state machine, as developed by Minsky. (See Ref. 4.) Ashby on the other hand captures the idea of a finite state machine by utilizing set theoretic terms according to which a "machine with input" is defined by set S of internal states, a set I of input states, and a mapping f of the product set IXS into S. See Ashby, "Principles of Self-Organizing Systems" in Principles of Self-Organization, von Foerster and Zopf (eds.), p. 261.

8. The paragraph above represents a gross over-simplification of various aspects of automata theory. The relevant references for more details are:

Minsky, M., Computation, Finite and Infinite Machines.

McCulloch, W. and Pitts, W., "A Logical Calculus of the Ideas Immanent in Nervous Activity," Bull. Math. Biophysics, 5 (1943); pp. 115-133, repr. in McCulloch, Embodiments of Mind.

Von Newmann, J., Theory of Self-Reproducing Automata, A. Burks (ed.).

Von Foerster, H., "Molecular Ethology," in Molecular Mechanisms in Memory and Learning, Ungar (ed.).

Pask, G., The Cybernetics of Human Learning and Performance.

Beer, S., Cybernetics and Management.

9. See Minsky, M., Computation, Finite and Infinite Machines.

10. See for example Petri, C. A., "Communication with Automata." Trans. by C. F. Greene. A supplement to Technical Documentary Report, 1, Rome Air Development Center Contract AF30(602)-3324 (1965); and Holt, A. W., "Final Report for the Information System Theory Project," Rome Air Development Center Contract AF30(602)-4211 (1968).

11. See for example Turing, A. M., "Computing Machinery and Intelligence" in Mind, 59 (1950); pp. 433-460.

12. Wiener, N., The Human Use of Human Beings, p. 27.

13. For a discussion of purpose and goal types in the context of feedback mechanisms, see Appendix C, Section C-7.

14. Pask, G., "Models for Social Systems and for Their Languages," Instructional Science, 1(4), (1973); p. 404.

15. Pask, G., "Some Mechanical Concepts of Goals, Individuals, Consciousness and Symbolic Evolution," a paper submitted in a Burg Wartenstein Symposium (1968); p. 20.

16. Miller, G. A., Galanter, E., and Pribram, K. H., Plans and the Structure of Behavior, p. 2.

17. McCulloch, W. S., "Agatha Tyche: Of Nervous Nets--The Lucky Reckoners" in Embodiments of Mind. Originally delivered at the Mechanization of Thought Processes; Proceedings of a Symposium held at the National Physical Laboratory, Nov. 1958.

18. Von Foerster defines a self-organizing system as a system (in which the rate of change of redundancy is always positive (see Appendix C, Section C-8.

19. For the implication of the concept of effective decision making see Beer, S., Brain of the Firm.

20. There are relatively few such major behaviors. McCulloch lists 15 modes for a typical vertebrate and 14 to

18 modes, depending on a specific viewpoing, for man. They include: sleeping, eating, drinking, fighting, fleeing, hunting, mating, urinating, and others.

21. McCulloch, W. S., "What is the brain that ink may character?" reprinted in Embodiments of Mind, pp. 387-397.

22. *Ibid.*, p. 397.

23. *Ibid.*, p. 397.

24. Pask, G., "The Cybernetics of Behavior and Cognition--Extending the Meaning of 'Goal'" International Congress of Cybernetics, London, Sept. 1969; p. 22.

25. *Ibid.*, p. 22.

26. See for example Pask, G., "Cognitive Systems"; also "Some Mechanical Concepts of Goals, Individuals, Consciousness and Symbolic Evolution" as well as "The Cybernetics of Behavior and Cognition Extending the Meaning of Goal," but especially "Models for Social Systems and for Their Languages."

27. Pask, G., "Models for Social Systems and for Their Languages," p. 404.

28. See Pask, G., "The Cybernetics of Behavior and Cognition Extending the Meaning of Goal," especially pp. 12-17.

29. See for example Pask, G., The Cybernetics of Human Learning and Performance, p. 55.

30. Pask, G., "Some Mechanical Concepts of Goals, Individuals, Consciousness and Symbolic Evolution," pp. 15-18.

31. Miller, G. A., Galanter, E., and Pribram, K. H., Plans and the Structure of Behavior.

32. See Boulding, K. E., The Image.

33. Miller, G. A., Galanter, E., and Pribram, K. H., Plans and the Structure of Behavior, p. 16.

34. *Ibid.*, p. 26.

35. *Ibid.*, p. 26.

36. *Ibid.*, p. 98.

37. See Appendix C, section C-9.

38. In this respect see for example the following:
   a. Hunt, E. B. and Hovland, C. I., "Programming a Model of Human Concept Formulation," pp. 310-325.
   b. Feigenbaum, E. A., "Simulation of Verbal Learning Behavior," pp. 297-309.
   c. Newell, A., and Simon, H. A., "A Program That Simulates Human Thoughts," pp. 279-296.

All in Computer and Thoughts, Feigenbaum, E. A., and Feldman, J. (eds.).

39. Miller, G. A., Galanter, E., and Pribram, K. H., Plans and the Structure of Behavior, p. 155.

40. Waddington, C. H., The Strategy of the Genes.

41. Bonner, J. T., The Evolution of Development.

42. Ibid., p. 38.

43. Bonner, J. T., "Control Programs in Biological Development" in Hierarchy Theory, H. Pattee (ed.).

44. Ibid., p. 65.

45. Quoted by Tinbergen, N., "Ethology (1969)" in The Animal in its World, pp. 143-144. This particular paper reviews the contemporary development of ethology. It acknowledges throughout the influence of cybernetics. See for example p. 141. But see also Mittelstaedt, "Control Systems of Orientation in Insects," Annual Rev. Ent. F. (1962).

46. See for example Tinbergen's description of the reproductive behavior in the stickleback fish. Tinbergen, N., The Study of Instinct.

48. Dubos, R., So Human an Animal.

49. A fascinating account is given by Von Frisch in The Dancing Bees.

50. Oswald, P. F., and Pelzman, P., "The Cry of the Human Infant" in Scientific American, March 1974.

51. There are numerous other theories, of course, for example those offered by von Foerster; Amosov; Fogel, Owens and Walsh; George; Newel, Shaw and Simons; Fiegenbaum; and others. Pask's work, however, is developed from the outset in cybernetic terms which are especially amenable to an interpretation in the domain of social processes.

52. Pask, G., "Cognitive Systems," p. 4. See also Ashby, "What is an intelligent machine?" BCL publication No. 44.

53. Pask, G., "Cognitive Systems," pp. 6-7.

54. Pask, G., "The Cybernetics of Behavior and Cognition, Extending the Meaning of Goal," p. 6.

55. *Ibid.*, p. 5.

56. Ashby, W. R., *Design for a Brain*.

57. For a detailed discussion see Pask, G., *Cognitive* Systems, pp. 4-7.

58. Pask, G., "The Cybernetics of Behavior and Cognition, Extending the Meaning of Goal," p. 22.

59. *Ibid.*, see especially pp. 13-17 on the distinction between "language oriented" and "taciturn" systems.

60. *Ibid.*, p. 6.

61. *Ibid.*, p. 6.

62. Ibid., p. 27.

63. Pask, G., "Cognitive Systems," p. 1.

64. Pask, G., "The Cybernetics of Behavior and Cognition, Extending the Meaning of Goal," p. 13.

65. Pask, G., "Cognitive Systems," p. 20. In this sense, see also Pask, G., "A cybernetic model for some types of learning and mentation," where the notion that the organization of learning can be regarded as "control of controls" is stressed.

66. See von Foerster, H., "Molecular Ethology," B. L. publication No. 184.

67. See Pask, G., "Cognitive Systems," especially section 1.5.

68. See Pask, G., "A cybernetic model for some types of learning and mentation." Also Pask, G., The Cybernetics of Human Learning and Performance, Chapter 6.

69. See Beer, S., Brain of the Firm.

70. Pask, G., "Models for Social Systems and for Their Languages," p. 432.

71. In addition to all the references which have already been cited in the context of this chapter, see the follow-

ing references for recent work embodied in operating teaching systems:

Pask, G., Kallikourdis, D. and Scott, B. C. E., "The Representation of Knowables," System Research (1974).

Pask, G., "The Nature and Nurture of Learning in a Social Educational System" presented at the Int. Symp. of Life-Long Learning in an Age of Technology. Turin (1973).

Pask, G. and Scott, B. C. E., "Learning Strategies and Individual Competence," System Research Ltd. (1970).

Pask, G. and Scott, B. C. E., "Uncertainty Regulation in Learning Applied to Procedures for Teaching Concepts of Probability," System Research Ltd. (1972).

Pask, G. and Scott, B. C. E., "CASTE: A System for Exhibiting Learning Strategies and Regulating Uncertainties," Int. J. Man-Machine Studies, 5:17-52 (1973).

Pask, G., Scott, B. C. E. and Kallikourdis, D., "A Theory of Conversation and Individuals Exemplified by the Learning Process on CASTE," Int. J. Man-Machine Studies, 5:443-566 (1973)

72. For a comprehensive classification of such models, see Pask, G., "Models for Social Systems and for Their Languages."

73. *Ibid.*, p. 408.

BIBLIOGRAPHY

Ackoff, R. L., "Games Decisions and Organization," in General Systems Year Book, Vol. 4 (1959), pp. 145-150.

Ackoff, R. L., "Systems, Organizations and Interdisciplinary Research," in Systems Thinking, Emery, F. E., ed., Penguin (1969).

Ackoff, R. L., "Towards a System of Systems Concepts," in Systems Behaviour, Beishon, J., Peters, G., eds., Open University Set Book, Harper and Row (1972).

Ackoff, R. L., Redesigning the Future, Wiley Interscience (1974).

Amosov, N. M., "Simulation of Thinking Processes," in Purposive Systems, 1st Annual Sympos. of ASC (1968), pp. 35-66.

Apter, M. J., Cybernetics and Development, Pergamon Press (1966).

Arnold, P., Aton, B., Rosenfeld, D., Saxena, K., and Von Foerster, H., "Diversity: A Measure Complementing Uncertainty," B.C.L. Report No. 84, University of Illinois, Urbana.

Ashby, W. R., "Design for an Intelligent Amplifier," in Automata Studies, Shannon, C. E., and McCarthy, J., eds., Princeton (1956), pp. 215-234.

Ashby, W. R., "General System Theory As a New Discipline," in General System Year Book, Vol. III (1958), pp. 1-6.

Ashby, W. R., "Requisite Variety and Its Applications for the Control of Complex Systems," in Cybernetica, Vol. 1, No. 2 (1958), pp. 53-99.

Ashby, W. R., "Principles of the Self-Organizing System," in Principles of Self-Organization, Von Foerster, H., and Zope, G. H., eds., Pergamon Press (1962), pp. 255-278.

Ashby, W. R., "The Self-Reproducing System," in Aspects of the Theory of Artificial Intelligence, Muses, C. A., ed., Plenum Press (1962).

Ashby, W. R., "The Set Theory of Mechanism and Homeostasis," Tech. Report No. 9, Electrical Engineering Research Laboratory, University of Illinois, Urbana (1962).

Ashby, W. R., "What Is an Intelligent Machine?" B.C.L. Publication No. 44, University of Illinois, Urbana.

Ashby, W. R., *An Introduction to Cybernetics*, Methuen - University Paperbacks (1964), (first published 1956).

Ashby, W. R., *Design for a Brain*, Chapman and Hall - Science Paperbacks (1966), (first published 1952).

Barricelli, N. A., "Numerical Testing of Evolution Theories," Part 1, in *Acta-Biotheoretica*, Vol. XVI-I/II (1962), pp. 69-98; Part 2, in *Acta-Biotheoretica*, Vol. XVI-III/IV (1963), pp. 100-126.

Bateson, C., *Our Own Metaphor*, Knopf (1967).

Bateson, G., *Steps to an Ecology of Mind*, Ballantine Books (1972).

Bateson, G., *Naven*, Stanford University Press (1973), (first published 1936).

Beer, S., "Towards the Cybernetic Factory," in *Principles of Self-Organization*, Von Foerster, H., and Zope, G. W., eds., Pergamon Press (1962), pp. 25-80.

Beer, S., *Decision and Control*, John Wiley & Sons (1966).

Beer, S., *Brain of the Firm*, Allen Lane (1972).

Beer, S., "Managing Modern Complexity," reprinted in *Cybernetics of Cybernetics*, B.C.L. Report No. 73.38 (1974), pp. 86-96.

Beer, S., *Cybernetics and Management*, English University Press (1971), (first ed. 1959).

Beer, S., *Designing Freedom*, John Wiley & Sons (1974).

Beer, S., *Platform for Change*, John Wiley & Sons (1975).

Bertalanffy, L. von, "The Theory of Open Systems in Physics and Biology," *Science*, Vol. III (1950), pp. 23-29. Reprinted in *Systems Thinking*, Emery, F. E., ed., Penguin (1969).

Bertalanffy, L. von, *Problems of Life: An Evaluation of Modern Biology and Scientific Thought*, Harper Torchbook (1960).

Bertalanffy, L. von, "General System Theory" reprinted in *General System Year Book*, Vol. 1 (1956), pp. 1-10.

Bertalanffy, L. von, *General System Theory*, George Braziller (1969).

Bohm, D., Causality and Chance in Modern Physics, University of Pennsylvania Press (1957).

Bonner, J. T., The Evolution of Development, Cambridge University Press (1958).

Bonner, J. T., "Control Programs in Biological Development" in Hierarchy Theory, Pattee, H. H., ed., George Braziller (1973), pp. 51-70.

Boulding, K. E., The Image, Ann Arbor: University of Michigan Press (1956).

Boulding, K. E., "Business and Economic Systems," in Positive Feedback, Milsum, J. H., ed., Pergamon Press (1968), pp. 101-117.

Bronowski, J., "New Concepts in the Evolution of Complexity: Stratified Stability and Unbounded Plans," in Zygon, Vol. 5 (1), (1970), pp. 18-35.

Bronowski, J., The Ascent of Man, Little, Brown & Co. (1973).

Burks, A. W., "Computation, Behavior and Structure in Fixed and Growing Automata," in Self-Organizing Systems, Yovits, M. C., Cameron, S., eds., Pergamon Press (1960), pp. 282-309.

Cannon, W. B., The Wisdom of the Body, Norton & Company (1963), (first published 1937).

Cherry, C., On Human Communication, M.I.T. Press (1970), (first published 1957).

Childe, V. G., Man Makes Himself, Mentor Books (1951).

Churchman, C. W., The Systems Approach, Delta (1968).

Cipolla, C. M., The Economic History of World Population, Penguin (1962).

Clarke, B., "The Cause of Biological Diversity," in Scientific American, Vol. 233, No. 2, August (1975), pp. 50-60.

Conant, R. C., "Information Transfer in Complex Systems with Application to Regulation," Tech. Report No. 13, Biological Computer Laboratory, University of Illinois, Urbana (1968).

Conant, R. C., "The Information Transfer Required in Regulatory Processes," in IEEE Trans. Systems Sci. and Cybernetics, Vol. 5, No. 4 (1969), pp. 334-338.

Conant, R. C., and Ashby, W. R., "Every Good Regulator of a System Must Be a Model of That System," in Int. J. Systems Sci., Vol. 1, No. 2 (1970), pp. 89-97.

Conrad, M., Pattee, H. H., "Evolution Experiments with an Artificial Ecosystem," in J. Theort. Biol. 28 (1970), pp. 393-409.

Craik, K., The Nature of Psychology, Sherwood, S., ed., Cambridge University Press (1966).

Dechert, C. R., "Integration and Change in Political and International Systems," in Positive Feedback, Milsum, J. H., ed., Pergamon Press (1968), pp. 118-138.

Dobzhansky, T., Mankind Evolving, Yale University Press (1962).

Dubos, R., So Human an Animal, Charles Scribner & Sons (1968).

Eigen, M., "Self-Organization of Matter and Evolution of Biological Macromolecules," in Die Naturwissenschaften, 58 (1971), pp. 465-523.

Emerson, A. E., "The Impact of Darwin on Biology," in Acta-Biotheoretica, Vol. XV-IV (1962), pp. 176-216.

Einstein, A., Out of My Later Years, Littlefield, Adams & Co. (1967).

Emery, F. E., (ed.), Systems Thinking, Penguin (1969).

Feigenbaum, E. A., Feldman, J., (eds.), Computers and Thought, McGraw-Hill (1963).

Feigenbaum, E. A., "Simulation of Verbal Learning Behavior," in Computers and Thought, Feigenbaum, E. A. and Feldman, J. (eds.), McGraw-Hill (1963), pp. 297-309.

Ferkiss, V., The Future of Technological Civilization, George Braziller (1974).

Fogel, L. J., Owens, A. J., Walsh, M. J., "Artificial Intelligence Through a Simulation of Evolution," in Biophysics and Cybernetic Systems, Maxfield, Callaghan and Fogel, L. J., eds., Spartan Books (1965), pp. 131-149.

Fogel, L. J., Owens, A. J., Walsh, M. J., Artificial Intelligence Through Simulated Evolution, Wiley (1966).

Forrester, J. W., Industrial Dynamics, M.I.T. Press (1961).

Forrester, J. W., "Modelling the Dynamic Processes of Corporate Growth," Proc. IBM Scientific Computing Symposium on Simulation Models and Gaming, Dec. (1964).

Forrester, J. W., Principles of Systems, Wright-Allen Press (1968).

Forrester, J. W., World Dynamics, Wright-Allen Press (1971).

Fuller, R. B., "Profile of the Industrial Revolution," W.D.S.D. document No. 3, S.I.U. (1965), pp. 27-33.

Fuller, R. B., Utopia or Oblivion, Banta Books (1969).

Fuller, R. B., Operating Manual for Spaceship Earth, S.I.U. Press (1969).

Fuller, R. B., Earth, Inc., Anchor Press (1973).

Fuller, R. B., Synergetics, Macmillan (1975).

Galbraith, J. K., Economics and the Public Purpose, Houghton Mifflin (1973).

George, F. H., "Logical Networks and Behavior," Bull. Math. Biophys., Vol. 18 (1956), pp. 337-348.

George, F. H., "Probabilistic Machines," Automation Progress, Vol. 3, No. 1 (1958).

George, F. H., Automation Cybernetics and Society, Leonard Hill Books (1959).

Glandsdorf, P., Prigogine, I., Thermodynamic Theory of Structure, Stability and Fluctuations, Wiley-Interscience (1971).

Glushkov, V. M., Introduction to Cybernetics, Academic Press (1966).

Goldman, S., "Further Considerations of Cybernetic Aspects of Homeostasis," in Self-Organizing Systems, Yovits, M. C., Camerson, S., eds., Pergamon Press (1960), pp. 108-120.

Grey, Walter W., The Living Brain, Penguin (1953)

Grobstein, C., "Hierarchical Order and Neogenesis," in Hierarchy Theory, Pattee, H. H., George Braziller (1973), pp. 31-47.

Hall, A. D., Fagen, R. E., "Definition of System," in General Systems Year Book, Vol. 1 (1956), pp. 18-28.

Heisenberg, W., Physics and Philosophy, Harper Torchbook (1962), (first published 1958).

Holt, A. W., "Information System Theory Project," Technical Report No. RADC-TR-68-305, Rome Air Development Center (1968).

Hunt, E. B., Hovland, C. I., "Programming a Model of Human Concept Formulation," in Computer and Thought, Feigenbaum, E. A. and Feldman, J., eds., McGraw-Hill (1963), pp. 310-325.

Huntington, E., Mainsprings of Civilization, Mentor Books (1945).

Huxley, T. H. and Huxley, J. S., Touchstones for Ethics, Harper (1947).

Jantsch, E., Design for Evolution, George Braziller (1975).

Jung, C. G., Modern Man in Search of Soul, Harvest Books, (first published 1933).

Katchalsky, A., Kedem, O., "Thermodynamics of Flow Processes in Biological Systems," in Biophysical Journal, 2 No. 2 (1962), pp. 53-78.

Katchalsky, A., "Thermodynamics of Flow and Biological Organization," in Zygon, Vol. 6 (2), (1971), pp. 99-125.

Katchalsky, A., Curran, P. F., Nonequilibrium Thermodynamics in Biophysics, Harvard University Press (1975).

Kaufman, S. A., "Metabolic Stability and Epigenesis in Randomly Constructed Genetic Nets," in J. Theort. Biol. 22 (1969), pp. 437-467.

Kerner, "Statistical Mechanics of Interacting Biological Species," Bull. Math. Biophys., 19 (1957).

Klir, J., Valach, M., Cybernetic Modelling, ILIFFE Books (1967).

Kohler, W., Gestalt Psychology, Menta Books (1959), (first published 1947).

Kuhn, T. S., The Structure of Scientific Revolutions, University of Chicago Press, 2nd ed. (1970).

Lang, O., Introduction to Economic Cybernetics, Pergamon Press (1970).

Laszlo, E., The Systems View of the World, Braziller (1972).

Laszlo, E., "A General Systems View of Evolution and Invariance," in General Systems Yearbook, Vol. XIX (1974), pp. 37-43.

Lerner, I. M., Genetic Homeostasis, Dover Publications (1970), (first published 1954).

Levi-Strauss, C., Totemism, Beacon Press (1963).

Löfgren, L., "Recognition of Order and Evolutionary Systems," in Computer and Information Sciences II, Tou, J., ed., Academic Press (1967).

Löfgren, L., "An Axiomatic Explanation of Complete Self-Reproduction," Bull. Math. Biophys., No. 30 (1968), pp. 415-424.

Löfgren, L., "Relative Explanation of Systems," in Trends in General Systems Theory, Klir, G., ed., Wiley (1972).

Lorenz, K., King Solomon's Ring, Methuen (1964).

Luria, S. E., Life the Unfinished Experiment, Charles Scribners Sons (1973).

Maturana, H. R., "Neurophysiology of Cognition," in Cognition: A Multiple View, Garvin, P., ed., Spartan Books (1970).

Maxwell, J. C., "On Governors," Proc. Royal Soc. of London, Vol. 16 (1868), pp. 270-283. Reprinted in Selected Papers on Mathematical Trends in Control Theory, Bellman, R., Kalaba, R., eds., Dover (1964).

McCulloch, W. S. and Pitts, W., "A Logical Calculus of the Ideas Immanent in Nervous Activity," Bull. Math. Biophysics, 5 (1943), pp. 115-133. (Reprinted in McCullock, W., Embodiments of Mind.)

McCulloch, W. S., "Finality and Form in Nervous Activity," Publication No. 11 in The American Lecture Series, Springfield, Ill.: Thomas, C. C. (1952). (Reprinted in McCulloch, W. S., Embodiments of Mind.)

McCulloch, W. S., "Agatha Tyche: Of Nervous Nets - The Lucky Reckoners," Mechanization of Thought Processes, Symposium at National Physical Laboratory, Nov. (1958). (Reprinted in McCulloch, W. S. , Embodiments of Mind.)

McCulloch, W. S., "What Is the Brain That Ink May Character?" presented at International Congress for Logic, Methodology and Philosophy of Science, Jerusalem, Israel, Aug. (1964). (Reprinted in McCulloch, W. S., Embodiments of Mind.)

McCulloch, W. S., Embodiments of Mind, M.I.T. Press (1970), (1st ed. 1965).

McCulloch, W. S., "Recollections of the Many Sources of Cybernetics," ASC Forum, Vol. VI, No. 2 (1974), pp. 5-16.

McHale, J., World Facts and Trends, Collier Books (1973).

Mead, M., Culture and Commitment, National History Press, Doubleday (1970).

Mesarovic, M., and Pestel, E., Mankind at the Turning Point, E. P. Dutton & Co. (1974).

Miller, G., Galanter, E., Pribram, K. H., Plans and the Structure of Behavior, Holt, Rinehart & Winston (1960).

Milsum, J. H., "Mathematical Introduction to General System Dynamics," in Positive Feedback, Milsum, J. H., ed., Pergamon Press (1968), pp. 23-65.

Minsky, M., "Steps Towards an Artificial Intelligence," Proc. I.R.E., 49 (1961), pp. 8-30.

Minsky, M., Computation, Finite and Infinite Machines, Prentice Hall (1967).

Mittelstaedt, H., "Control System of Orientation in Insects," Annual Rev. Ent. F. (1962).

Myhill, J., "The Abstract Theory of Self-Reproduction," in Essays on Cellular Automata, Burks, A. W., ed., University of Illinois Press (1970), pp. 206-218.

Newell, A., Shaw, J. C., Simon, H. A., "A Variety of Intelligent Learning in a General Problem Solver," in Self-Organizing Systems, Yovits, M. C. and Cameron, S., eds., Pergamon Press (1960), pp. 153-189.

Newell, A. and Simon, H. A., "A Program That Simulates Human Thoughts," in Computer and Thought, Feigenbaum, E. A. and Feldman, J., eds., McGraw-Hill (1963), pp. 279-296.

Oswald, P. F., Pelzman, P., "The Cry of the Human Infant," in Scientific American, March (1974).

Pask, G., "Teaching Machines," Proc. 2nd Int. Conf. on Cyb. Namur (1958).

Pask, G., "Physical Analogues to the Growth of a Concept," in Mechanization of Thought Processes, Utley, A., ed., HMSO (1959).

Pask, G., "The Natural History of Networks," in Self-Organizing Systems, Yovits, M. C. and Cameron, S., eds., Pergamon Press (1960), pp. 232-263.

Pask, G., "A Proposed Evolutionary Model," in Principles of Self-Organization, Von Foerster, H., Zope, G. W., eds., Pergamon Press (1962), pp. 229-253.

Pask, G., "The Cybernetics of Evolutionary Processes and Self-Organizing Systems," Proc. 3rd Cong. Inter. Assoc. of Cybernetics, Namur, Gauthier Villars, ed., (1965), pp. 27-75.

Pask, G., "Comments on an Indeterminancy That Characterizes a Self-Organizing System," in Cybernetics of Neural Processes, National Research Council, Rome (1965).

Pask, G., "Comments on the Cybernetics of Ethical, Sociological Systems," in Progress in Biocybernetics, Vol. 3 (1966), pp. 158-280.

Pask, G., An Approach to Cybernetics, Hutchinson (1968), (first published 1961).

Pask, G., "Some Mechanical Concepts of Goals, Individuals, Consciousness and Symbolic Evolution," a paper delivered at a Burg Wartenstein Symposium on "The Effects of Conscious Purpose on Human Adaptation," July (1968).

Pask, G., "A Cybernetic Model for Some Kind of Learning and Mentation," in Cybernetic Problems in Bionics, Oestreicher, M. C. and Moore, D. R., eds., Gordon & Breach (1968).

Pask, G., "The Cybernetics of Behaviour and Cognition Extending the Meaning of 'Goal'," System Research Ltd., paper delivered at the International Congress of Cybernetics, London (1969).

Pask, G., "The Computer-Simulated Development of Populations of Automata," in Mathematical Biosciences, 4 (1969), pp. 101-127.

Pask, G., "Cognitive Systems," in Cognition: A Multiple View, Garvin, L., ed., Spartan Press (1970).

Pask, G., Scott, B. C. E., "Learning Strategies and Individual Competence," Final Report, SSRC Project HR 983/1, System Research Ltd. (1970).

Pask, G., Scott, B. C. E., "Uncertainty Regulation in Learning Applied to Procedures for Teaching Concepts of Probability," Final Report, SSRC Project HR 1203/1, System Research Ltd. (1972).

Pask, G., "Models for Social Systems and for Their Languages," Instructional Science, 1 (4), (1973), pp. 395-445.

Pask, G., Scott, B. C. E., Kallikourdis, D., "A Theory of Conversation and Individuals (Exemplified by the Learning Process on CASTE)," Int. J. Man-Machine Studies, 5 (1973), pp. 443-566.

Pask, G., Scott, B. C. E., "CASTE: A System for Exhibiting Learning Strategies and Regulating Uncertainties," Int. J. Man-Machine Studies, 5 (1973), pp. 17-52.

Pask, G., "The Nature and Nurture of Learning in a Social Educational System," presented at the Int. Symp. of Life-Long Learning in an Age of Technology, Turin (1973).

Pask, G., Kallikourdis, D., Scott, B. C. E., "The Representation of Knowables," System Research Ltd. (1974).

Pask, G., The Cybernetics of Human Learning and Performance, Hutchinson (1975).

Pattee, H. H., Hierarchy Theory, George Braziller (1973).

Pattee, H. H., "The Physical Basis and Origin of Hierarchical Control," in Hierarchy Theory, Pattee, H. H., ed., George Braziller (1973), pp. 73-108.

Penrose, L. S., "The Supposed Threat of Declining Intelligence," Am. J. Mental Deficiency, 53 (1948), pp. 114-118.

Petri, C. A., "Communication with Automata," (Trans. by Greene, C. F.), a supplement to Technical Documentary Report, 1, Rome Development Center, Contract AF 30(602)-3324 (1965).

Porter, A., Servomechanisms, Methuen Physical Monographs (1950).

Prigogine, I., "Structure, Dissipation and Life," in Theoretical Physics and Biology: Proceedings, Marois, M., ed., North-Holland Publishing Co. (1969), pp. 23-52.

Prigogine, I., Nicolis, G., "Biological Order, Structure and Instabilities," Quarterly Review of Biophysics, 4, 2 & 3 (1971), pp. 107-148.

Prigogine, I., Nicolis, G. and Babloyantz, A., "Thermodynamics of Evolution," in Physics Today, Nov. (1972), pp. 23-28, Dec. (1972), pp. 38-44.

Rapparort, R., Pigs for the Ancestors, Yale University Press (1968).

Rashevsky, N., Mathematical Biophysics, Dover (1960).

Reed, J., Toombs, R., Barricelli, N. A., "Simulation of Biological Evolution and Machine Learning," in J. Theoretical Biol., 17 (1967), pp. 319-342.

Reiser, O. L., The Integration of Human Knowledge, Porter Sargent (1958).

Reiser, O. L., Cosmic Humanism, Schenkman Publishing (1966).

Reynolds, V., The Biology of Human Action, Oxford University Press (1976).

Rosenblueth, A., Wiener, N., Bigelow, J., "Behavior Purpose and Teleology," Phil. of Sci., Vol. 10 (1943), pp. 18-24.

Rosenblueth, A., Wiener, N., Bigelow, J., "Purposeful and Nonpurposeful Behavior," Phil. of Sci., Vol. 17 (1950), pp. 318-326.

Rothman, M. A., The Laws of Physics, Pelican (1963).

Schilpp, P. A., (ed.), Albert Einstein, Philosopher Scientist, Vol. 1, Pen Court Classics (1969).

Schrödinger, E., What Is Life? Cambridge University Press (1967), (first published 1944).

Shakespeare, W., Hamlet, Washington Square Press.

Shannon, C. E., Weaver, W., The Mathematical Theory of Communication, University of Illinois Press (1969), (first published 1949).

Simon, H. A., "The Architecture of Complexity," Proc. American Philosophical Society, 106, Dec. (1962), pp. 467-482.

Simon, H. A., "The Organization of Complex Systems," in Hierarchy Theory, Pattee, H. H., ed., George Braziller (1973), pp. 3-27.

Simpson, G. G., The Meaning of Evolution, Bantam Books (1971), (first published 1947).

Siu, R. G. H., The Tao of Science, M.I.T. Press (1957).

Slobodkin, L. B., "Animal Population and Ecologies," in Positive Feedback, Milsum, J. H. ed., Pergamon Press (1968), pp. 149-163.

Sommerhoff, G., Analytical Biology, Oxford University Press (1950).

Sommerhoff, G., "The Abstract Characteristics of Living Systems," in Systems Thinking, Emery, F. E., ed., Penguin (1969), pp. 147-202.

Stanley-Jones, D. & K., The Kybernetics of Natural Systems, Pergamon Press (1960).

Szent-Gyorgyi, A., The Crazy Ape, Grosset & Dunlap (1970).

Teilhard de Chardin, P., The Phenomenon of Man, Harper Torchbooks (1965), (first published 1955).

Teilhard de Chardin, P., The Future of Man, Harper Torchbooks (1969).

Tinbergen, N., The Study of Instinct, Oxford University Press (1951).

Tinbergen, N., The Animal in Its World, Vol. 1 & 2, Harvard University Press (1975), (first published 1972).

Toynbee, A., A Study of History, (Abridged Edition), Weathervane Books (1972).

Toynbee, A., Mankind and Mother Earth, Oxford Univ. Press (1976).

Turing, A. M., "Computing Machinery and Intelligence," in Mind, 59 (1950), pp. 433-460.

Uttley, A. M., "The Classification of Signals in the Nervous System," EEG Clin. Neurophysiology, Vol. 6 (1954), pp. 479-494.

Varela, F. G., Maturana, H. R., Uribe, R., "Autopoiesis: The Organization of Living Systems, Its Characterization, and a Model," Biosystems, 5, North Holland Publishing Co. (1974), pp. 187-196.

Von Foerster, H., "Basic Concepts of Homeostasis," BCL Publication No. 5, reproduced from: Homeostatic Mechanisms, Brookhaven Symposia in Biology, No. 10 (1957), pp. 216-242.

Von Foerster, H., "On Self-Organizing Systems and Their Environments," in Self-Organizing Systems, Yovits, M. C. and Cameron, S., eds., Pergamon Press (1960), pp. 31-48.

Von Foerster, H., "Communication Amongst Automata," in The American Journal of Psychiatry, Vol. 118, No. 10, April (1962), pp. 865-871.

Von Foerster, H., "Biological Principles of Information Storage and Retrieval," B.C.L. Publication No. 150. Reprinted from Electronic Handling of Information: Testing and Evaluation, Kent, Taubee, Beltzer & Goldstein, eds., Academic Press (1967), pp. 123-147.

Von Foerster, H., "Molecular Ethology," in Molecular Mechanisms in Memory and Learning, Ungar, C., ed., Pergamon Press (1970).

Von Foerster, H., "Cybernetics at Illinois," ASC Forum, Vol. VI, No. 2 (1974), pp. 21-22.

Von Frisch, The Dancing Bees, Harcourt, Brace (1955).

Von Neumann, J., "Probabilistic Logic and the Synthesis of Reliable Organisms from Unreliable Components," Automata Studies, Princeton University Press (1956).

Von Neumann, J., Theory of Self-Reproducing Automata, Burks, A., ed., University of Illinois Press (1969).

Waddington, C. The Ethical Animal, Atheneum (1961).

Waddington, C. H., "Human Ideals and Human Progress," in World Review, August (1946), pp. 29-36.

Waddington, C. H., The Strategy of the Genes, George Allen and Unwin (1956).

Wiener, N., Cybernetics, M.I.T. Press (1965), (first published 1948).

Wiener, N., The Human Use of Human Beings, Avon Books (1967), (first published 1950).

Wiener, N., "Cybernetics," Scientific American, No. 179 (1948), pp. 14-18.

Wilkins, L., Social Deviance, Tavistock (1963).

Wynne-Edwards, W. C., Animal Dispersion in Relation to Social Behavior, Oliver & Boyd (1962).

Young, J. F., Cybernetics, ILIFFE Books (1969).

Zadeh, L. A., "Towards a Theory of Fuzzy Systems," Aspects of Network and System Theory, Kalman, R. E. and De Claris, N., eds., Holt, Rinehart & Winston (1971).

Zadeh, L. A., "Outline of a New Approach to the Analysis of Complex Systems and Decision Processes," in IEEE, Transactions on Systems, Man, and Cybernetics, Vol. SML-3, No. 1, Jan. (1973), pp. 28-44.