

### 3 Aspects of Evolution and Reproduction

are all hardware revisions more fundamental than increasing the number of tapes so that descriptions are no longer *linear* (permitted already in Chapter 2). It should be emphasised that these are not the only rephrasings of the theory in current use; others are due to Baricelli (1962), Glushkov's associate Letichevsky (cited in Glushkov, 1966), Toda (1962), Apter (1966), Penrose (1962), Codd (1968), Kauffman (1971), and my own group (reported below and in Pask, 1969a).

**1.2 Tessellation Models** The tessellation model, in particular, is very interesting as a curiously aseptic and 'simple' form of representation, and it has recently been shown to be possible (Vityani, 1973) to represent a wide variety of reproductive systems in this manner (various kinds of sexual reproduction, immune response systems, and so on). A very lucid account of self-reproduction is given by Moore (in Burks, 1970, essay 6). The following notes form an overview, not an explanation.

A tessellation is an infinite plane of cells, each containing a finite-state machine with a distinguished 'quiescent' state. The planar configuration is inessential (a 'cube' or an  $n$ -fold figure would do as well, or better if it could be as easily depicted); it is essential, however, that the cells are neighbourhood-indexed in a plane by rows and columns. The finite-state machines are synchronously clocked, each changing state at fixed intervals  $t = 1, 2, \dots$  and the state of any one of these machines (i.e. these cells) at  $t + 1$  depends upon the state of its neighbours and itself at  $t$ . Thus the neighbours provide an *input*. The detailed assignment of neighbours is not critical; for example all adjacent cells may be neighbours of any one cell (as in Moore's essay) or a more limited set of cells may be neighbours. However, the neighbours must be adjacent in the tessellation indexing scheme. Further, the entire tessellation must be homogeneous in the sense that if a transition rule is specified to show how the state of a cell depends upon the states of its neighbours, then this has the same meaning for all cells (Fig. 20). As a result of executing the process determined by the constraints of the tessellation, the initial condition and the chosen transition rule, certain configurations of active and inactive cells are produced, one configuration is matched to another if the two can be superimposed, state for state, by translation on the tessellation plane. In so far as this condition applies, the two configurations are *copies*. A configuration is self-reproducing, if some interval  $t + \tau$  can be chosen for any value of  $t > 0$ , such that it generates copies and these copies are contained as disjoint within it.

The *configuration* is the entity which reproduces. The finite-state machines and their organisation in the tessellation plane is the hardware *in which* this piece of software *reproduces*. Of course, the picture can be inverted (to say that certain state sequences, for example, are reproduced in the software

Computer theorists make a distinction between the 'hardware' and 'software' aspects of a system. The hardware includes the physical constituents (whether the machine is really made in the flesh or the metal) and also the structures either permanently or characteristically attached to the *processor*, such as compiler routines and the organisation of data storage in words, blocks, etc. The software is the program. To preserve the realisability of arbitrary TM and TU in equivalent programs/tape descriptions we insist that the storage *capacity* is potentially unlimited.

#### 1 Hardware-Software Equivalence

For any machine, it is possible to trade off hardware for software and/or vice versa provided the restrictions do not prohibit the existence of a general abstract machine. Various authors refer to somewhat different general abstract machines; for example Burks (1970, essay 2) calls it a 'control automaton' while Chiaraviglio, Hagen and Roehkase (1972) call it an 'iterative abstract computer'. One important point is that such a thing can be given an indefinite number of hardware realisations, so that the trade off is very general. In this sense, which is much stronger than talking about dependence upon physical bits and pieces, abstract machines can be said to be hardware independent.

**1.1 Equivalences in Respect of Reproduction** The theory of self-reproducing abstract machines is *hardware independent*. For example, the self-reproduction outlined in the last chapter is kinematic. It is argued, for example, in Burks (1970), that such a formulation runs into undue levels of complexity when it comes to specifying the *parts* and how they are arranged to be 'generally available'. It is possible to rephrase the theory without losing any of the properties discussed (*not*, however, as the reader will note in the reference, without loss of *some* possibilities) in terms of *tessellation automata*, or, in general, *cellular automata* which include, for example, Holland's iterative circuit computers (Burks, 1970, last three essays). These

equivalent of the program <initial states, transition rule> generating the configuration). However, the intended interpretation and the convenient one is as specified.

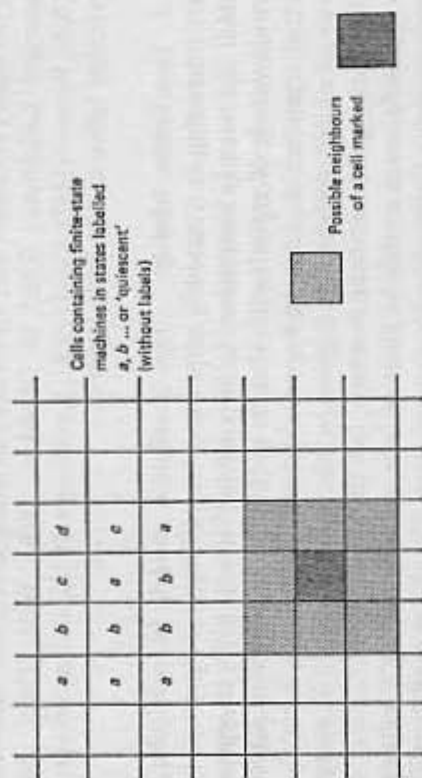


Figure 20 Features of a tessellation plane.

**1.3 Primitive Evolutionary Machines** Our own work on reproduction and evolution was instigated by the curious dendritic computing systems reported in my book (Pask, 1961a) and in Pask (1959). They make use of a model which superficially resembles the tessellation model (for example, there is an infinite plane and there are configurations). The structures to be described, in outline, are more closely related to Toda's models or some of Apter's. In common with Toda and Apter, the work was undertaken in order to elucidate certain aggregation and exclusion processes manifest both at a social and a cellular level.

**1.4 Some Interpretations** For example, Wilkins (1963) postulated a form of social homeostasis; inherently stable roles differentiate and are stabilised due to mass aggregation and group pressure against deviance from the norms that go along with these roles (e.g. common occupations such as 'labourer' or 'squire' and orientations such as 'self-centred' or 'keeping up with the Joneses'). Moreover, if these roles are viewed as self-replicating *organisations* in a social group, it should be possible to adjust norms by the introduction of appropriately selected deviant individuals, thus either establishing a fresh norm or switching between potentially available, though not necessarily manifest, old norms. At the cellular level similar effects are manifest in connection with differentiation and immune reactions.

More specific simulations were also performed as part of the project which extended over six years or more, on and off (Pask, 1961b). For example, it was possible, by introducing signalling mechanisms that mirrored the biological signalling substance, acrasin, to mimic the behaviour of populations of cellular slime moulds. These are colonial amoebae with a life-cycle involving (1) a phase of unicellularity; (2) a phase of aggregation of the unicells along chemical gradients to form a partly differentiated 'slug'; (3) a phase of motility as the slug; (4) a phase in which certain cells in the 'slug' form a stalk and others spores; and (5) rupture of the spores to produce further unicellulars.

Only the more general results are used as illustrations in the present discussion.

**1.5 Consideration of Pure Machine Evolution** The models consisted in machines. To some extent, they were viewed as populations of machines with no particular interpretation attached to them. However, when conceiving them in this way our attention was focussed upon the evolutionary, rather than the replicative, activity of the machine population. This attitude, combined with the requirement to simulate some social/biological systems, determined a much more complex and less tractable design than the tessellation model. The design is thoroughly inelegant (for our interest was not primarily mathematical) but the models exhibit most of the additional features set aside on moving from the *kinematic* to the *tessellation* model for self-reproduction.

With certain qualifications, the work will be described in a way that seemed appropriate when it was carried out; many of the notes are culled from contemporary reprints and publications. But, with rather small modifications, it is possible to convert the evolutionary models of those days into systems that are similar to those that image strategy and concept learning, viewed as a kind of symbolic evolution which takes place in the brain as a processor. These developments are surveyed in the present volume but not properly discussed until the next.

## 2 Background for Abstract Models

A model for evolution involves the environment in which evolution occurs, as well as that which evolves. With respect to organisms that evolve, or a species or single organism, the environment will be a physical structure in which there is food to consume and form to perceive and the companionship of other organisms. When one considers brain activities that evolve, the environment will be sequences of messages in various languages and various modalities. To machines, the environment is composed of other



machines, parts for them, and a supply of negentropy. These environments, and, for that matter, many others, can be represented as abstract constraints (called 'food' or 'neighbourhood', but only as convenient ways of talking about abstractions). The abstract constraints can be identified with a variety of different environments or the attributes of different evolving entities. But these interpretations will appear more or less plausible, to the extent that some may become impractical and others become imperative, at different stages in the evolutionary process. As a consequence, there is a structural uncertainty regarding what it is that does evolve—the organism, an aggregate of organisms, or the process of development of each individual.

**2.1 Conditions for Evolution** 1. In the real world, evolution occurs when there are distinct elements each of which can survive in certain conditions of the environment and not in others. The issue of whether or not a particular element does survive in conditions that permit its survival depends upon its behaviour, and in any interesting process the behaviour of the elements must be such that they tend to remain in existence. Survival of the *structured* physical material that constitutes the element is a prerequisite of the stability of the organisation that maintains the element, commonly by resynthesis of structural components from raw material ('food') in the environment. Thus, conversely, survival depends upon stability. Cells are typical elements in the biological environment (though it would be possible to cite the reaction centres of some autocatalytic reactions or regions of activity in a network of artificial neurones as perfectly legitimate evolving elements in different environments). For cells, the survival of the energy-transforming mechanism is a prerequisite for maintaining the nucleic acids that chiefly determine the cellular organisation.

2. Survival is conditional. The simplest conditionality occurs if 'food' is available in short supply. In this case 'food' is a source of available negentropy and it can be read as 'money' or 'electric current' or any other convertible commodity without altering the essential condition that, if it is restricted there will be competition between the elements for whatever is available.

3. Either the elements must be capable of reproduction on their own account, given success in the 'food competition', or there must be a locally specified state of the environment such that one element is created when the local 'food concentration' is high (a 'nucleation' process) or both.

4. The reproductive mechanism may take many different forms and act at many different levels, for characteristically, it evolves also. In biology this is Bonner's (1958) thesis, the 'evolution of development'; in genetic evolution it is part of Waddington's (1957) thesis. So it would perhaps be

more accurate, to assert a 'principle of reproduction' as the requirement. 'Reproduction', in any case, means a little more than 'replication', in the sense of creating accurate images of the ancestor. The process of reproduction (at whatever level it is realised) may be imperfect due to ambiguity and the resulting offspring may include variants upon the original.

It is customary to consider an active source of variation as a prerequisite of evolution; for example, genetic mutation. Here the only variation is due to the resolution of ambiguity.

5. Unlimited development of a population is restricted by the rate of influx of the locally conservable commodity, given the code name 'food'. To make sense of this statement there must be a *principle* (in the present arrangement it is manifest in various *mechanisms*) that gives an advantage to some types and configurations of automata over other types.

6. The environment of the automata is so designed that if there are many of them in an aggregate then an aggregate in which the actions of automata are correlated is at an advantage, and such an aggregate (a coalition of cooperatively interacting automata) is replicating in the environment. It plays the same role as a *configuration* on the tessellation plane, but is not the same *thing* as a configuration. It may or may not be the case that the co-existing *coalitions* cooperate as well.

7. For the sake of uniformity we were anxious to embed a similar property in the most elementary constituents, i.e. the automata. One method, due chiefly to D. J. Feldman (and used in model I, below) is a recognition criterion. An automata can recognise what it *does*, retain a record of this activity and, if it encounters an ambiguous situation that requires choice, it resolves the ambiguity by preferring the same activity. Another method (used in model II below) is to assign the cooperative property to complementary *pairs* of automata that are of different *types* and have different possible actions built into their repertoire.

8. Given these conditions inflow of 'food' into the 'environment' initiates a process of evolution wherein elements, once created, tend to form increasingly organised aggregates and successful variants tend to be selected and reproduced.

**2.2 Specific Evolutionary Models** During the project, many different models were tried out. Two classes of model (I and II) are described and outline flow charted in Appendix D. In model I, there is one complex type of automaton; in model II, there are several simple types which may be composed according to combination and mating rules. In model I the recognition criteria of section 2.1 (number 7) are embodied as part of the automaton and constitutes a mutual cooperation or replication principle. In model II the cooperation is a distributed property of types. Both classes of

model satisfy the requirements of section 2.1 (number 3) by mating and copying (a form of reproduction) though other models incorporated nucleation as well.

The following comments on behaviour are based upon between seventy and eighty simulations. The work is dated by the fact that the simulations were run on an ICT 1202 programmed in machine language. Feldman showed great ingenuity in augmenting the limited storage capacity by externally sorting cards representing the automata and machine checking the card-sorter output.

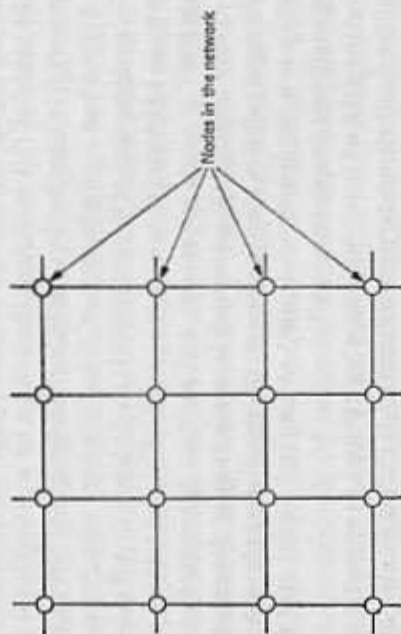


Figure 21 Nodes.

**2.3 A Specific Evolutionary Model** The environment is a lattice of the kind shown in Fig. 21. Other topologies (toroidal, infinite plane and so on) are possible. Each node in Fig. 21 is a point at which 'food' becomes available and where one of the evolving elements or (as it is convenient to call them) automata, can sit and feed. The connections in the lattice are pathways along which automata can move from one node to another. The possible movements of the automata are shown in Fig. 22 (type \* only is relevant to model I, all other types to model II).

The structure imposed upon the environment is a set of pathways or nodal connections and a rule for delivery of food which is conveniently visualised through Fig. 23. Each node (indexed  $k$ ) is associated with a 'node bucket' (level  $u_k$ ) filled with food through a constricted aperture. When an automaton (indexed  $i$ ) rests at a node (indexed  $k$ ) it eats food from the node bucket and stores it in a bucket of its own (a 'stomach') with level  $\theta_i$ . It eats food faster than the speed that this commodity is replaced through the aperture. As a result, the automaton is bound to move. The most elementary linear motions for any type of automaton are shown in Fig. 24.

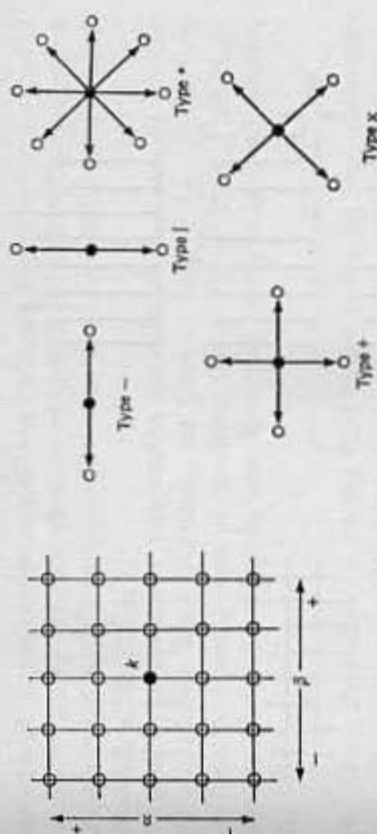


Figure 22 Indexing of node  $k$  in environment (far left) and possible motions of automata of different types situated at this node.

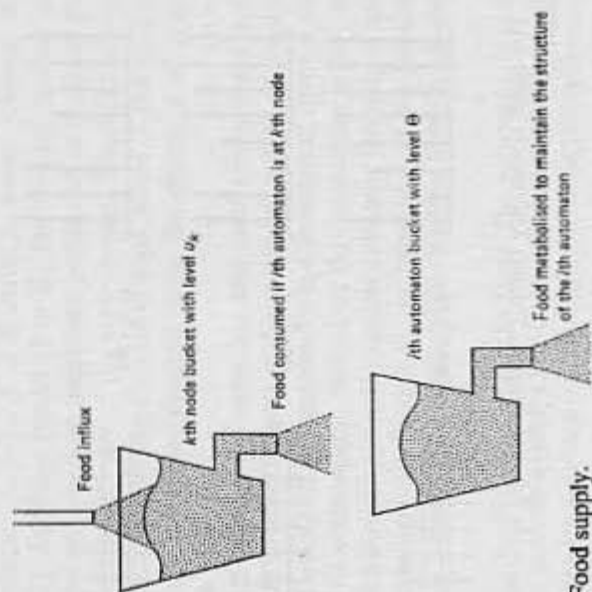


Figure 23 Food supply.

As food flows into the environment, the  $u_k$  increases unless there is an automaton to eat the food. If an automaton exists at node  $k$ , the food is depleted (to pay for the automaton's fabric). All automata are designed to survive in the sense that, other things being equal, they can inspect the nodes to which they can move and actually move towards the best stocked region. Sometimes there is no ambiguity. For example, consider an automaton at node  $a$  able to move to node  $b$  or node  $c$ .

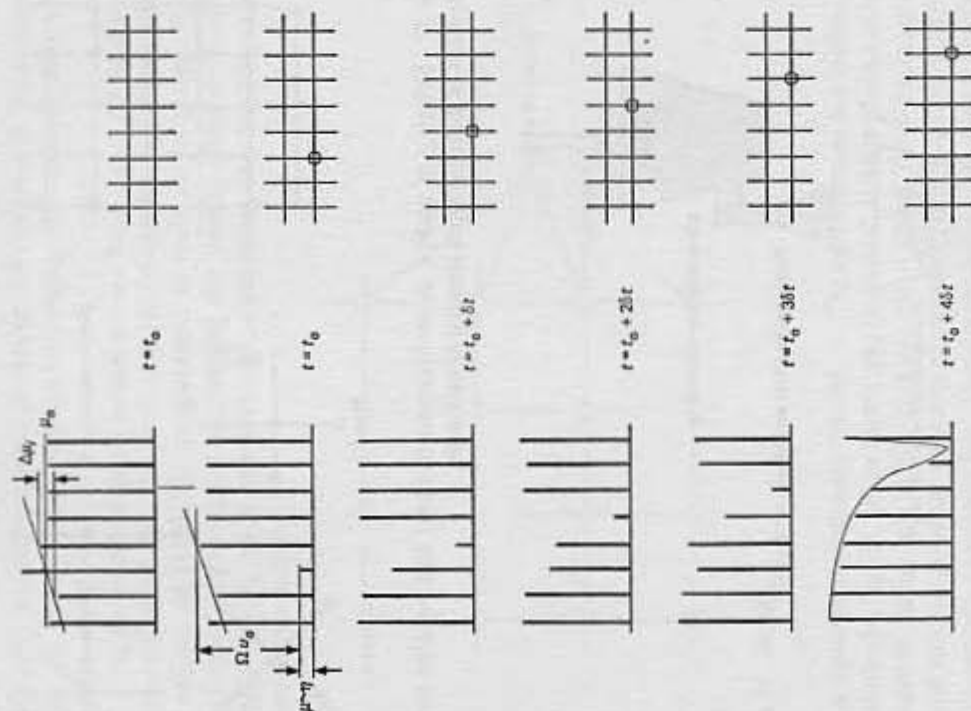


Figure 24 The most elementary (linear) motions for any type of automaton (models I and II).

If  $u_b > (u_a \text{ or } u_c)$  it moves to  $b$ ,  
 If  $u_c > (u_a \text{ or } u_b)$  it moves to  $c$ ,  
 If  $u_a > (u_b \text{ or } u_c)$  it remains motionless.

If  $u_b = u_c$  the situation is ambiguous. Either  $u_b = u_c > u_a$  when the automaton *should* move but has no direction determined or  $u_a > u_b = u_c$  when it remains motionless. Though a move into the same place is apparently determined, the rate at which the stomach content,  $\theta$ , must be metabolised to pay for an automaton is set higher than the influx rate; so here,

also, there is an impasse. In model I the ambiguity is resolved at the level of the automaton by invoking the recognition criterion (the learned preference weights in the model). In model II it is only resolved at the level of combinations of automata.

Apart from parameter assignments (considered in Appendix D) the initial conditions for a simulation are given (at step O) by  $u_i(0)$  (always uniform) by a distribution of automata (either ten or twelve, randomly disposed about the thirty-six central nodes) and for each automaton,  $i$  by  $\theta_i(0)$ .

**2.4. Gross Properties** As the food inflow builds up food concentration at the nodes, automata move about and combine with one another. In model II there is, on average, an advantage in the combination  $A \circ B$ , but this rule may be contradicted in regions that are populated by a particular species of automaton (for example, in a region populated by the combination  $A \circ A$ ,  $B \circ B$  have a better chance of survival than  $A \circ B$ ). In either model (I or II) the feeding pattern of the prevalent species induces a characteristic pattern upon the food distribution over the nodes in this part of the environment. The mean population size initially depends only upon the rate of food inflow. Later in development the mean population size depends upon the efficiency of aggregates or coalitions as well.

Interaction between the automata and their environment is due to the fact that a behaviour induces a characteristic pattern of food depletion. Now the behaviour of any automaton is a function of its own state and of the state of its environment. But where this interaction is very strong due to the concerted activity of many similar automata the state of the environment is increasingly determined by the behaviour of the population, and as a result, the automata form groups in which the individuals play specialised roles.

Even at an earlier stage, the activity of the automata is cooperative, since pairs of automata behave in a fashion that increases their joint chance of survival (the behaviour would be impossible for the individuals alone). The action of the isolated automata that constitute the pair is correlated. The mechanism sensitive to food concentration has begun to serve a different function, which it reasonably can in these conditions, namely that of a communication mechanism whereby one automaton senses the presence of the other in terms of food depletion. The 'storage' capacity needed to rationalise this statement resides in the inertial characteristics of the environment.

Successful coalitions of automata, linked in this fashion, are reproduced here (Fig. 25, for model I, Fig. 26 for model II). But a population may or



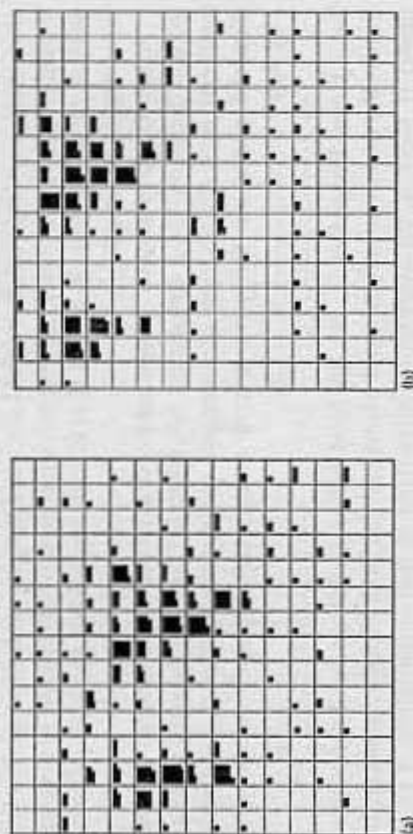


Figure 25 Distribution of type 'a' automata in environment: (a) step fifty in simulation; (b) step sixty in simulation (ten steps later).

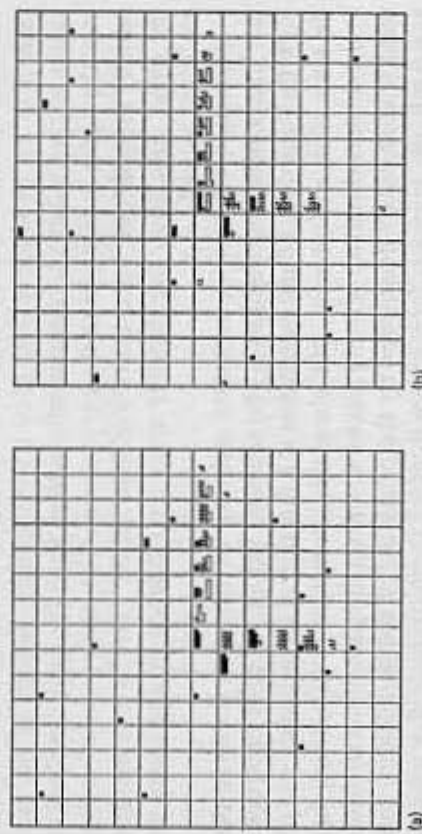


Figure 26 Distribution of automata in environment: (a) step fifty in simulation; (b) step sixty (ten steps later).

may not survive; this depends upon the food influx rate and upon an inherent stability (measured as sensitivity to decrements in food inflow).

The development of *norms* can be followed in macroscopic terms by examining clusters of values of vital statistics (for example, the mean of motion weights in Fig. 27) which indicate homeostasis and mass action upon deviants (section 1.4). But salient clusters reflect an underlying configuration of the cooperative and replicating type.

If the density of a stable configuration of automata becomes high enough there is a very interesting discontinuity in its structure, reminiscent of crystallisation. Although the group moves about as a whole and modifies

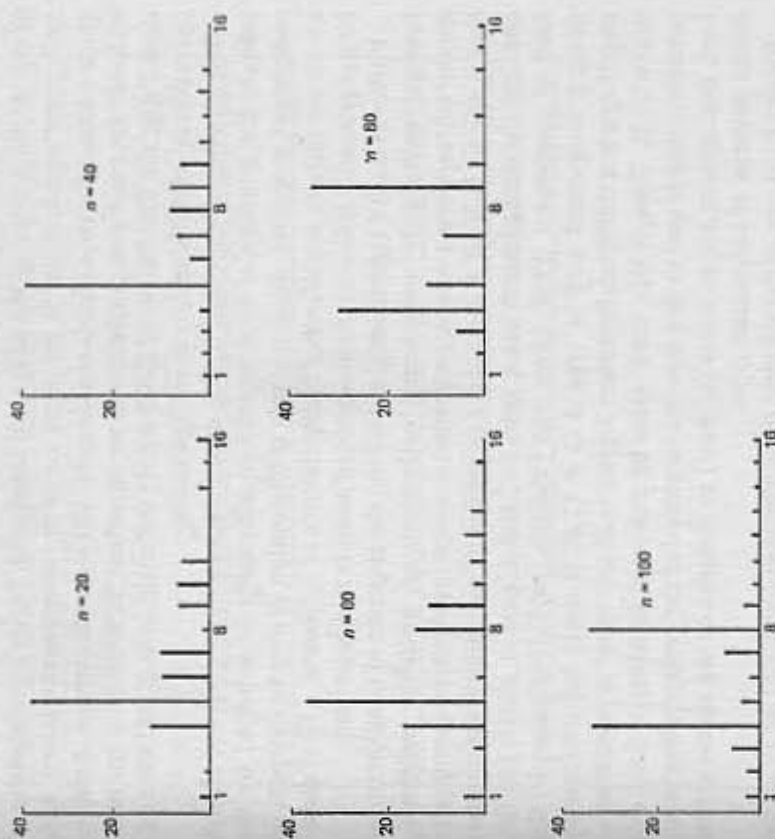


Figure 27 Histograms showing the evocation of a novel norm. The abscissa represents the ratio of horizontal to vertical movement weights and the ordinate the number of automata characterised by each ratio value.

the environment where it resides, any individual has a behaviour that is invariant relative to its neighbours. Some individuals, for example, behave as units in a transmission line composed of a chain of automata, such that movement of one induces food depletion that induces a completely determined movement of the next automaton. Transmission lines have a critical role in the stability of the group since they act as elements in a 'nervous system' that determines a direction of movement for the group as a function of the food available in other parts of the environment (sensed by the relatively unrestricted activity of the outermost automata), and the food available internally.

Regarded as a stable entity, which it is, the *configuration* is aiming to survive in the context of other configurations in a common environment. It makes 'decisions' with this object. It is thus reasonable to ask what is maximised by the group 'decision rule' (by analogy with the  $\theta$  maximisation

of the 'decision rules' of the individual automata). Surely a prerequisite of any group 'decision rule' is maintenance of the components, hence, adequate  $\theta$  values for the individual automata. But a simple average 'quantity of food' does not seem to be the most important factor, and it has been shown that the *distribution* of food, within the environment that the configuration inhabits, is usually more significant.

The *distribution* as sensed by the outermost automata does not always indicate the quantity of food which can ultimately be collected by the component automata. Since a stable configuration is able to compete or cooperate with, or engulf, other configurations of automata, a food distribution primarily indicates the existence of another configuration.

Rather extensive experiments, examining the response of configurations towards deliberately introduced collections of unviable automata, empirically supported the contention that incipient instability in a configuration is due to lack of a component (a species of elementary automaton) and that the configuration has a 'need for' and a 'goal to search for' this kind of component (Pask, Lewis and Feldman, 1965). For example, the missing component may be type  $A \circ A \circ B$ ; it could be obtained by engulfing a less stable configuration replete with this type<sup>1</sup> or by cooperation with it. Though this 'need' could be expressed in terms of food distributions that is not, in fact how it is *described* at the configuration level; here, descriptions are in terms (at least) as complex as the characteristic action patterns of automaton types.

Results from one of the simplest experiments of this kind (the *induction* of a specific change) are shown in Figures 28 and 29 (a control experiment) using the type II model. In a free running simulation, mechanisms of the kind proposed appear to be responsible for a number of ubiquitous phenomena. One of them is shown in Fig. 30. It may either be interpreted as a predator prey interaction, the population phenomena analysed by Kerner (1959), or as the explicit symptom of a primitive immune response, notably in the sense of Bell (1973). Certainly, the oscillatory interaction can be suppressed by actions that are designed to density regulate the reproduction of the configuration *constituents* counting as prey or the *configuration* counting as an alien organisation.

**2.5 Retrospective Identification** Suppose that the stable configurations of automata are identified as the reproducing/evolving entities. (As pointed out earlier, this is a matter for choice; several options are open to the experimenter.)

1. In other models by engulfing a configuration having a more complex type, say  $(A \circ A \circ B) \circ (A \circ B)$  that is decomposable into the required type.

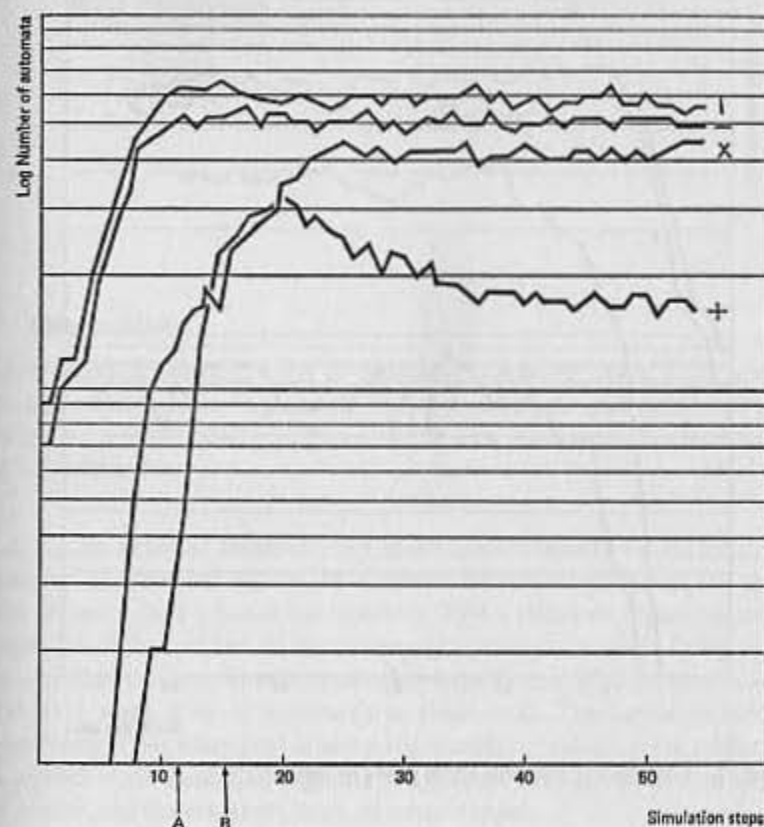


Figure 28 Induction experiment, types |, -, +, and x.

Suppose the configurations *do* correspond, in this model, to configurations on a tessellation plane. If so, the environment is *not*, under that correspondence, analogous to the tessellation plane. The processor that executes the configuration is a population of automata (adapted automata in model I, or automata of different types in model II). Hence, the analogous 'tessellation plane' is neither homogeneous nor invariant. Moreover the characteristics of this processor are prone to modification by the process undergoing execution.

## 4 Relativism

### 1 Observation

Most scientific writing, even in behavioural science, takes it for granted that an observer can, in principle, act as a numinous and unbiased entity called an external observer. This point of view is embedded in part but not all of system theory.

**1.1** An external observer may make measurements, to determine the state of an observed system for example. Should he partition the system (for instance, into a 'black box' (Ashby, 1964c) called an organism and another 'black box' called its environment) he comes, by dint of observation or auxiliary data, to entertain detailed hypotheses. Though of course, he did have some kind of hypothesis to begin with. The organism is worth observing; it has some goal or some characteristic behaviour; it, rather than a myriad other candidate organisms, has been distinguished from the flux of events and chosen apart from its environment.

The detailed hypotheses ultimately arrived at are causal. The organism and the environment are conceived as certain kinds of machine. The observer believes, with certainty or just statistically, that each output was caused by some input, or some input/output history. Conversely, he may act upon the organism in a special manner or he may build the environment, as an experimental regulator, in order to do so. In this case, he entertains the predictive hypothesis that an input will cause a certain output or output sequence.

**1.2** Moreover, the external observer is causally related to the system under observation; he necessarily conceives it impersonally and refers to it as *it*. One useful consequence of this fact is that he can consistently entertain the notion that the system has, in principle, a state and that one, and only one, state occurs at once. The state transitions are ordered, and this order is interpreted as temporal ordering and can be determined by an observational clock. Its internal clock may be synchronised with this clock in

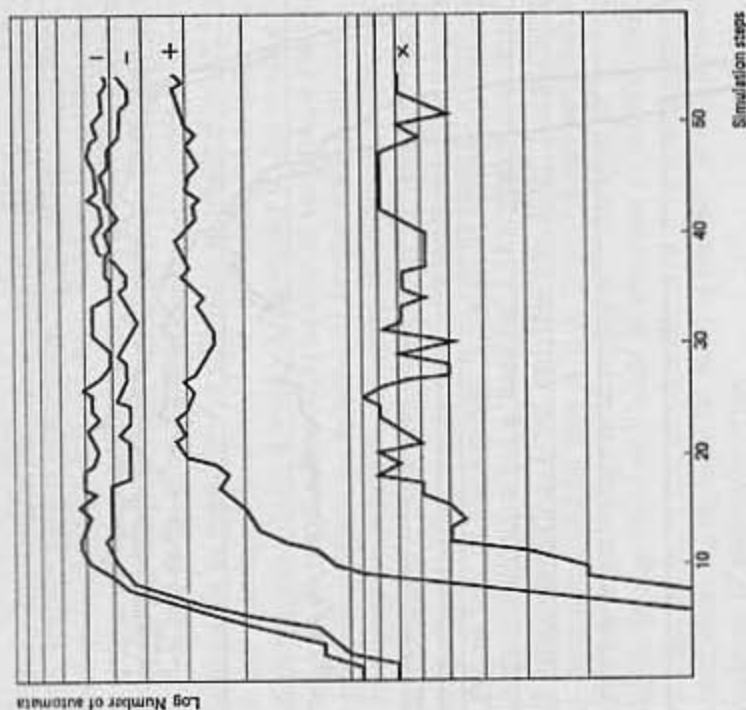


Figure 29 Control experiment, types |, -, + and x.

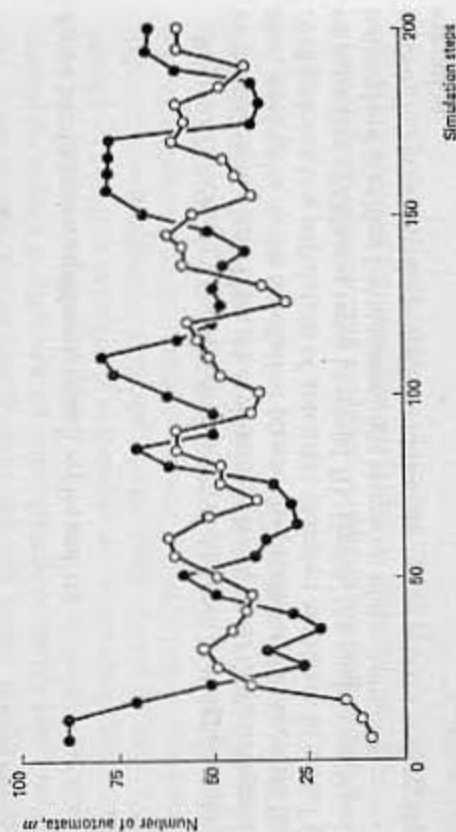


Figure 30 Oscillatory interaction between complex (+ or x) and simple (| or -) automata: |, - or x automata; + or -.