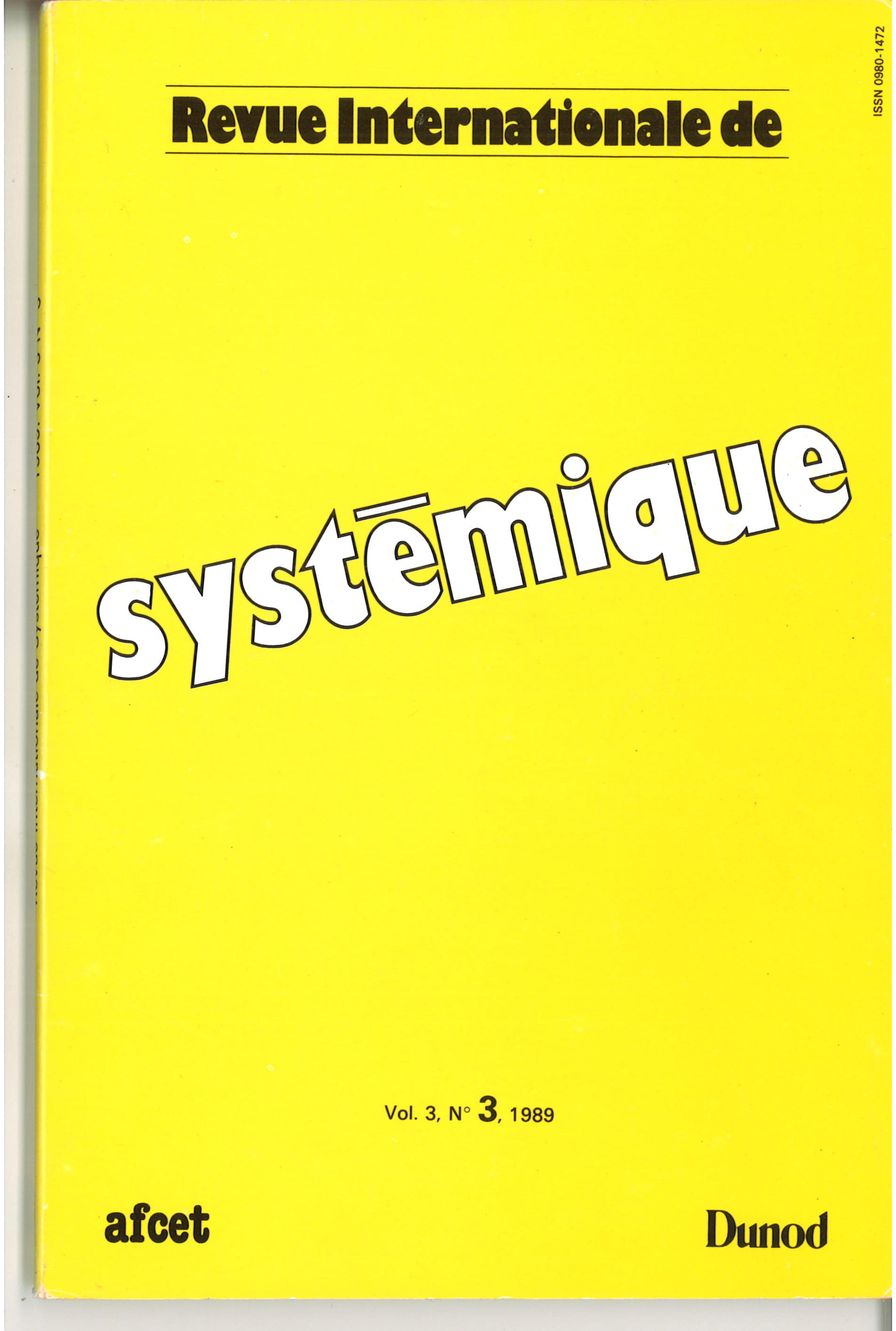

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Statistical machinery

W. Ross Ashby

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STATISTICAL MACHINERY *

W. ROSS ASHBY

Cet article, de même que celui de Warren S. McCulloch et celui de Louis Couffignal, reproduits, pour le premier, à la rubrique « Archives » de la *Revue Internationale de Systémique* (vol. 1, n° 3, 1987) et, pour le second, à la même rubrique de la même revue (vol. 2, n° 1 et n° 2, 1988), est emprunté au numéro de *Thalès* (tome 7, année 1951, paru en 1953, Presses Universitaires de France) consacré à la cybernétique et réalisé avec la collaboration du *Cercle d'Etudes Cybernétiques* (1949-1953) que nous avions fondé. Ce numéro spécial de la revue *Thalès*, organe officiel de l'*Institut d'Histoire des Sciences et des Techniques de l'Université de Paris*, dont le Directeur était alors Gaston Bachelard et le secrétaire général Pierre Ducassé, contenait aussi d'autres textes, consacrés à la cybernétique, et dus à N. Rashevsky, F. Russo et R. Vallée.

En 1951 W. Ross Ashby était Directeur du Département de la Recherche à Barnwood House (Gloucester, Grande-Bretagne). L'un de ses ouvrages fondamentaux *Design for a brain* (Chapman and Hall, Londres, 1952) était encore sous presse. Il devrait être suivi par *An introduction to cybernetics* (Chapman and Hall, Londres, 1956 ; traduction française : *Introduction à la cybernétique*, Dunod, Paris, 1958).

Ashby est connu, en particulier, pour sa « loi de la *diversité nécessaire* » (requisite variety), perfectionnée par son élève Roger C. Conant. Le « principe » qui fait appel à la fois à des concepts de la théorie de l'information et de la théorie des jeux, dans un cadre cybernétique, est l'un des premiers à lier cognition et action. C'est encore à Ashby et à Conant que l'on doit l'idée, parfois contestée, que « tout bon régulateur d'un système doit être un modèle de ce système » (1969). Ashby s'est trouvé aussi à l'origine, dès 1946, de l'idée d'« auto-organisation ».

*Texte publié dans *Thalès*, tome 7, année 1951 (paru en 1953), pp. 1-7. Nous remercions les Presses Universitaires de France de nous avoir autorisés à reproduire ce document.

C'est aussi à l'*homéostat* et à ses dérivés qu'est souvent attaché le nom de Ashby. Le texte présenté ici se situe dans cette ligne de recherche où dans des modèles, réels ou conceptuels, la *complexité* et le *déterminisme* engendrent des évolutions quasi-imprévisibles, d'aspect *chaotique*, d'où peuvent émerger des traits «statistiques» simples. Ces modèles peuvent conduire à la description de comportements d'*apprentissage*, d'*adaptation* et de *sélection «darwinienne»* de ceux-ci.

On remarquera que l'allusion faite dans l'article à Boyle concerne, comme il est bien connu, ce que l'on appelle, dans les pays de langue française, la loi de Mariotte (dont Boyle possède l'antériorité).

Robert Vallée

During the last few years it has become apparent that the concept of "machine" must be very greatly extended if it is to include the most modern developments. Especially is this true if we are studying the brain and attempting to identify the type of mechanism that is responsible for the brain's outstanding powers of thought and action. It has become apparent that when we used to doubt whether the brain could be a machine, our doubts were due chiefly to the fact that by a "machine" we understood some mechanism of very simple type. Familiar with the bicycle and the typewriter, we were in great danger of taking them as the type of all machines. The last decade, however, has corrected this error. It has taught us how restricted our outlook used to be ; for it developed mechanisms that far transcended the utmost that had been thought possible, and taught us that "mechanism" was still far from exhausted in its possibilities. Today we know only that the possibilities extend beyond our farthest vision.

Everyone now knows how the introduction of "feedback" has enabled machines to be self-correcting and thereby to show how the body also is self-correcting. Less noticed, however, was the introduction of the "statistical" element into machinery. The "homeostat" [1], for instance, has demonstrated that the deliberate introduction of randomness into a machine, with suitable corrective feedback, can give a flexibility of action and a power of adaptation not seen before. Further developments of the homeostat have shown how important is the randomness and how different

1 Ashby (W. Ross), The cerebral mechanisms of intelligent action, in *Perspectives in Neuropsychiatry*, edited D. Richter, H.K. Lewis & Co., London, 1950.

from ordinary machines are those that use it. As these new machines have properties hitherto not seen in ordinary machines, I propose to give an outline of what is developing. A detailed account is being published elsewhere [1].

Here I shall show how randomness can be introduced into machines, what are the main consequences of its introduction, and how the new facts can help us to understand the nervous system.

To get a clear starting point, let me outline the classic case of statistical mechanics, for the history of this branch of science gives us some guidance in what to expect.

After Newton had shown how to compute the trajectories of two bodies moving under their mutual attractions, it was a natural step to try to find the trajectories of three, four, ... n bodies. The "three-body" problem proved very difficult, the "four-body" even worse, and the "n-body" beyond all solving. But it was found that as the number of bodies was increased, so did new simplicities appear, simplicities that culminated in the laws of Boyle and of Charles. Statistical mechanics, then, showed clearly that disorder sufficiently increased can lead to the emergence of statistical order.

With this example of what to expect we can examine the possibility of making machinery so complicated that no one can follow its course in detail. Suppose we take some parts that can interact, thermionic valves or neurons for instance, join them at random, and then ask what will happen. If the number of parts is small a detailed calculation may give the answer ; but as the number of parts is increased so does the calculation become difficult and then impossible. Suppose, however, that we go on and make the number of interacting parts ever greater ; in some cases it will happen that we shall observe the emergence of statistical order and simplicity. These simplicities may be as useful scientifically as those discovered by Boyle and Charles. Modern mechanisms, in fact, are beginning to explore these statistical possibilities.

Such a machine can be at once determinate and statistical. Lest it should be thought that there is some inherent incompatibility let me be more explicit. The machine is determinate if every part in it acts in a perfectly determinate way in relation to those other parts with which it is

1 Ashby (W. Ross), *Design for a Brain* (In the press), Chapman & Hall, London.

functionally connected. Such a machine can also be statistical in the sense that the number of parts and the complexities of their interactions allow no other approach than the statistical.

The statistical element may be introduced in several ways. Perhaps some features of the machine's construction can be specified only statistically, so that any particular machine shows in its construction only the results of a particular random sample. Such would happen if thermionic valves, varying somewhat in characteristics, were to be used in large numbers in a machine that was affected by their differences. Or it would occur if a network of parts were joined at random, so that a particular network would show only a random sample of the possible patterns of joining. Another way in which the statistical element can be introduced into a machine occurs if the machine retains many effects, "memories", carried over from its past history. It may then happen that when it produces some behaviour, the behaviour is affected by memories that can be specified only statistically.

The cerebral cortex has probably a statistical aspect for all these reasons. First, the cerebral cortex is so complex in its microscopic details that we cannot suppose them all to be adjusted to exact values with the accuracy of a machine built to a blue-print. A large proportion of these details can only be determined in a statistical sense. Similarly in its connexions there must be much that is arranged at random, especially in the finest details. Again, the cortex of the adult contains, at any moment, so many memory-traces left by its past experience that its behaviour in any new situation can be related only statistically to the pattern of traces.

The selfswitching network

So far, what I have said would apply to the ordinary machine that is not quite exact but is allowed the usual engineering "tolerance". Such a machine might be said to be "statistical" to a slight degree. But it is not of this that I write. I want to consider the machine in which the statistical element has become the major factor in its behaviour.

Let us build a machine in the following way. Let the parts have some uniformity so that they need not be specified individually but only statistically. Let them be joined by a method or in a pattern that is defined only statistically. Let the system be very large, so that statistics that are subject to variation from random sampling, such as averages, are almost error-free. And let the system be observed only statistically, so that only averages, or other statistics, not the details, are seen.

Such systems are not as uncommon as might at first be thought. In addition to the cerebral cortex there are examples to be found in physical, meteorological, social and economic systems. At a very simple level the homeostat shows something of the statistical element, for its behaviour at any particular trial will depend in detail on the positions at which the uniselectors ("stepping-switches") were left after the previous trial. This dependence on its previous history introduces something of the statistical element for, unless we observe the details in its mechanism, we cannot predict exactly how many trials it will take on a particular test, though we *can* make statistical statements such as that a particular problem needs, on the average, two trials while another problem needs, on the average, twelve.

In order to explore the possibilities of such statistical machinery, an experimental machine (D.A.M.S. : Dispersive And Multistable System) is now being constructed at Barnwood House [1]. Thermionic valves provide the active parts, and each receives inputs from, and gives outputs to, several others. They can be joined into a network either wholly at random, or at random subject to restrictive conditions. Feedback is usually allowed unrestrictedly. Neon lamps provide the "memory" and act as switches. The valves determine whether or not the neon lamps shall strike ; and the neon lamps, by their striking, determine the patterns of interaction among the valves.It is, therefore, in a sense, self-switching. Apart from the fact that the system seems to invite total disorder, there are two facts that emphasize D.A.M.S., unusual character. First, the machine is indifferent to a small number of mistakes in its construction. The failure of a few valves, the cutting of a few wires, the crossing-over of a few connexions are of no importance, for the main statistical tendencies proceed almost unaffected. In this it resembles the homeostat, which would obviously be unaffected had the randomised wirings on the uniselectors been replaced by other randomised wirings (for, though the behaviour would have been quite different in detail, the tendency of the homeostat to adapt would have been unaffected). A second peculiarity of D.A.M.S.is that it requires that its component parts do not resemble each other too closely, for exact resemblance would have resulted in, say, all the neons being lit or all being unlit with no variety in the combinations. It had, therefore, deliberately to be built of parts of low accuracy.

1 Gloucester, England.

D.A.M.S. contains one feature that was specially introduced because of its high theoretical importance and because of its wide-spread occurrence in the nervous system – The parts of which D.A.M.S. is built are often inactive, becoming active only when certain conditions arise in the other parts that affect them. Such "part-functions" are common in the nervous system, where the phenomenon of "threshold" ensures that each nerve cell will become active only if the stimulation that comes to it exceeds some definite level.Part-functions occur, too, in any machines whose parts are "amplitude-limited", i.e. which cannot take values outside a certain range. Such a part will remain constant over any time-interval in which its surrounding parts force it to the extreme value and hold it there.

Such a self-switching system, cortex or D.A.M.S. or other, if large and built of part-functions, will show certain characteristic properties no matter in what random pattern the parts are joined together and no matter in what state its "memories" have been left by previous activities. It can be shown [1] that any system of part-functions consists of a number of loosely-coupled sub-systems whose couplings vary with time and with the state of the machine. A first statistical property of a self-switching network is that *these sub-systems tend to be many and small rather than few and large*. For consider the machine after it has gone to one of its many equilibrial states. If it is disturbed at some point, and shows its stability by a tremor from which it returns to the equilibrial state, the tremor, by hypothesis, will not disturb all the variables of the machine. If now we draw a map of the network, and mark the portion affected by the particular tremor and notice how many variables have been affected, then this number tends to be small. The reason is that the probability that a system should be stable tends to diminish exponentially as the number of variables in the system increases [1]. Large random assemblies of active variables have, therefore, little chance of being stable. So they tend to break up by destroying the pattern of switches that formed them. Small assemblies, however, are often stable, so they have less tendency to change the pattern of switches that formed them. There is thus a perpetual tendency for the large systems to disintegrate and for the small to persist. The result is a bias towards small systems.

In the cerebral cortex such a tendency would have clearly identifiable consequences, which can be interpreted in terms of the theory already

1 Ashby (W. Ross), The stability of a randomly assembled nerve-network, *E.E.G. Clin. Neurophysiol.*, 2, 471-482 (1950).

given for the homeostat. It would result in the organism tending to adapt to its environment, or to solve its problems, part by part, analytically. Such a tendency is of some practical importance. An environment, or problem, that is unsolvable if treated as a single entity, may be easily solvable if it can be analysed into parts and each part treated independently. The fact that the problem-solver instinctively proceeds analytically, if that is possible, may be an expression of this property of a statistical mechanism.

The second statistical property of a self-switching network is that *if the network is repeatedly disturbed by a regular "stimulus" or by a statistically homogeneous "noise", it will tend to set its switches so that it is less, rather than more, disturbed by it*. The property has been demonstrated on the homeostat [1] and is already showing on the partly-constructed D.A.M.S. It depends on the fact that patterns that are much disturbed by the stimulus will have a large chance of being disrupted, while those that are little disturbed will have only a small chance of being disrupted. Every stimulus or noise thus tends differentially to disrupt those patterns that are specially sensitive to it. The end-result is that the machine tends, if repeatedly stimulated, to become unresponsive to the stimulus.

In the cerebral cortex this phenomenon has long been known as "habituation". It is in fact not restricted to the cerebral cortex but can be observed in every tissue that is capable of learning. Humphrey [2] considers it to be the most fundamental form of learning. It may be significant that this basic form of learning is also a property of the self-switching system. There is a possibility, too, that the same property may contribute towards an explanation of the conditioned reflex. Some experiments of the author's have confirmed the possibility ; but the question requires extensive investigation before a definite conclusion can be reached.

In general it will be seen that though the study of statistical machinery has hardly begun, it has already yielded results of some interest.

"Darwinian" processes in machinery

The reader will have noticed that the properties of the self-switching network were found by considering the turmoil that may exist in such a system and then asking "what can survive" ? The answer is bound to be of

1 Ashby, *Design for a Brain*, p. 100.

2 Humphrey (G.), *The nature of learning*, London, 1933.

high importance in the study of these systems, for a pattern that cannot survive, that is merely a transient between others, can hardly be of major importance, while one that persists will dominate the picture of the machine and will force its characteristics into prominence. In this respect the self-switching network and a biological system under Darwinian natural selection show a profound similarity in their developments in time and in the emergence of characteristic features, for in each the emphasis is not on the question "what can happen" ? but on the question "what can survive" ? In each the statistical element is a major factor : we ask not what will happen but what will probably happen. In each there is free action and interaction between the component parts. In each there is apparent chaos. And in each there is the same fundamental tendency to adaptation, of form in the species and of learned behaviour in the self-switching network. The parallelism is, in fact, so close that Wiener has suggested [1] that such machines should be called "Darwinian", for this word, better than any other, describes their essential mode of action.

The analogy between the well understood processes of natural selection and those that occur in large statistical machines is likely to be of great value in the further study of these machines, for the "classic" methods become useless and one is forced to look for new. The classical method for studying a machine is to identify the actions of the parts and then construct, step by step, a theory of how they will act in unison. But when the number of parts is increased without limit this method becomes totally impossible. It is then that the analogy with the processes of natural selection becomes most valuable, especially since the method becomes more, not less, accurate as the size of the machine is increased.

The method has, for instance, been applied to elucidate the events that occur in the cerebral cortex not only when learning occurs but when more and more learning is accumulated in the same system with only a statistical control over its distribution. If the learning, as adaptation, follows essentially the principle used by the homeostat, we would have to consider a machine built out of thousands, or even millions of homeostats, all learning and adapting, and interacting and upsetting each other by their activities. It might well be thought that such a system was doomed to perpetual and inescapable chaos. Nevertheless there is good reason to believe [2], that here, as elsewhere, total disorder leads to the emergence of

1 Wiener (Norbert), personal communication.

2 Ashby, *Design for a Brain*, chapitre 18.

statistical order. There is good reason to believe that such a system is essentially self-coordinating – that it has a strong tendency, like a species subjected to natural selection, to eliminate the non-adaptive reactions and to preserve the adaptive. If this is so, then the steady progress of the brain, from the confusion and inefficiency of childhood to the coordination and efficiency of adulthood, would receive an explanation, at least in outline.

The picture of the cerebral cortex, then, to which we are led is one in which the microscopic details are as dynamic and as chaotic as the collisions of molecules in a gas. But though the cortex is chaotic in these details chaos does not rule everywhere. When we observe the whole man we see nothing of these details, we see only statistical properties. Because these properties come from the activities of very large numbers – the human cortex contains over 10^9 neurons – they show a continuity and orderliness very different from the chaos on which they are based.

We are led, therefore, to the conclusion that man does not think logically – he thinks dynamically.