

The System with Local Stabilities

13/1. HAVING examined what is meant by a system that has 'partial, fluctuating, and temporary independencies within the whole' we can now consider some of the properties that a system of such a type will show in its behaviour.

In saying 'a system of such a type' we have not, of course, defined a system with precision: we have only defined a set or class of systems. How shall we achieve precision? Two ways are open to us.

One way is to add further details until we have defined a particular system with full precision, so that its behaviour is determinate and uniquely defined; we then follow the behaviour in all detail. Such a study would give us an exact conclusion, but it would give us far more detail than we require, or can conveniently handle, in the remaining chapters.

Another way is to talk about such systems 'in general'. Here nothing is easier than to relax our grasp and to talk vaguely about what will 'usually' happen, regardless of the fact that whether particular properties (such as linearity, or the presence of thresholds) are 'usually' present differs widely in the systems of the sociologist, the neurophysiologist, and the physicist. Rigour and precision are possible while speaking of systems 'in general' provided two requirements are met: the *set* of systems under discussion must be defined precisely, and statements made must be precise statements about the properties of *the set*. In other words, we give up the aim of being precise about the individual system, and accept the responsibility of being precise about the set. This second way is the method we shall largely follow in the remaining chapters.

Having changed to the new aim, we shall often find that the argument about the set is conducted most readily in terms of some individual system that is followed in detail; when this happens, the individual system must be understood to have

importance only as a typical, generic, or 'random' element of the set it belongs to. Though the argument will often appear verbally to be focused on an individual system, it is directed really at the properties of the set, the individual system being introduced only as a means to an end.

We shall have much to do, in what follows, with systems constructed in some 'random' way. The word will always mean that we are discussing some *generic* system so as to find its *typical* properties, and thus to arrive at some precise deduction about the defined *set* of systems.

13/2. A set of systems of special importance for the later chapters is the set of those systems that are made of parts that have a high proportion of their states equilibrating, and are made by the parts being joined at random.

More precisely, assume that we have before us a very great number of parts, assumed to be fairly homogeneous, so that there is a defined 'universe', or distribution, of them. Each is assumed to be state-determined, and thus to have in it *no randomness whatever*. As a little machine with input, if it is at a certain state and in certain conditions it will do a certain thing; and it will do this thing whenever the state and conditions recur.

We now take a sample of these parts by some clearly defined sampling process and thus arrive at some particular set of parts. (It is not assumed that all parts have an equal probability of being taken.) Again we take a sample from the possible ways of joining them, taking it by a clearly defined sampling process, and thus arrive at some one way of joining them.

The particular set of parts, joined in the particular way, now gives the final system.

This particular final system, be it noticed, is state-determined. It is *not* stochastic in the sense of being able, from a given state and in given conditions, to undergo various transitions with various probabilities. Thus the *particular* system is not random at all. The randomness enters with the observer or experimenter; he is little interested in the particular system taken by the sampling, but is much interested in the population from which the particular system has come, as the neurophysiologist is interested in the set of mammalian brains. The 'randomness' comes in because the observer faces a system that interests him

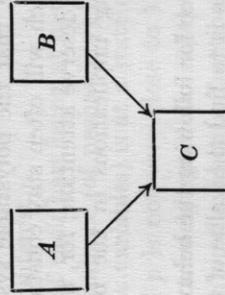
only because it is typical of the set. With the population as his sample space (derived from the two primary sample spaces) he may then legitimately speak of the *probability* of the system showing a certain event, or having a certain property.

If to this specification we add the restriction that the original parts are rich in states of equilibrium (e.g. as in S. 12/15), we get a type of system that will be referred to frequently in what follows. For lack of a better name I shall call it a **polystable** system. Briefly, it is any system whose parts have many equilibria and that has been formed by taking parts at random and joining them at random (provided that these words are understood in the exact sense given above).

Definitions can only be justified ultimately, however, by their works. The remainder of the book will demonstrate something of the properties of this interesting type of system, a key-system in the strategy of S. 2/17.

13/3. In such demonstrations we shall not be discussing one particular system, specified in all detail: we shall be discussing a set. When a set is discussed we must be careful to keep an important distinction in mind, and *we* must make the distinction arbitrarily: (1) are we discussing what *can* happen?—a question which focuses attention on the extreme possibilities, and therefore on the rare and exceptional; or (2) are we discussing what *usually* happens?—which focuses attention on the central mass of cases, and therefore on the common and ordinary. Both questions have their uses; but as the answers are often quite different, we must be careful not to confuse them.

13/4. A property shown by *all* state-determined systems, and one that will be important later is the following. In a state-determined system, if a subsystem has been constant and then commences to show changes in its variables, we can deduce that



among its parameters must have been, when it started changing, at least one that was itself changing. Picturesquely one might say that change can come only from change. The reason is not difficult to see. If variable or subsystem C is affected immediately only by parameters A and B , and if A and B are constant over some interval, and if, within this interval, C has gone from a state c to the same state (i.e. if c is a state of equilibrium), then for C to be consistent in its behaviour it must continue to repeat the transition ' c to c ' so long as A and B retain their values, i.e. so long as A and B remain constant. If C is state-determined, a transition from c to some other state can occur only after A or B , for whatever reason, has changed *its* value.

Thus a state-determined subsystem that is at a state of equilibrium and is surrounded by constant parameters (variables of other subsystems perhaps) is, as it were, trapped in equilibrium. Once at the state of equilibrium it cannot escape from it until an external source of change allows it to change too. The sparks that wander in charred paper give a vivid example of this property, for each portion, even though combustible, is stable when cold; one spark can become two, and various events can happen, but a cold portion cannot develop a spark unless at least one adjacent point has a spark. So long as one spark is left we cannot put bounds to what may happen; but if the whole should reach a state of 'no sparks', then from that time on it is unchanging.

Progression to equilibrium

13/5. Let us now consider how a polystable system will move towards its final state of equilibrium. From one point of view there is nothing to discuss, for if the parts are state-determined and the joining defined, the whole is a state-determined system that, if released from an initial state, will go to a terminal cycle or equilibrium by a line of behaviour exactly as in any other case.

The fact, however, that the polystable system has parts with many equilibria, which will often stay constant for a time, adds special features that deserve attention; for, as will be seen later, they have interesting implications in the behaviours of living organisms.

13/6. A useful device for following the behaviour of these somewhat complex wholes is to find the value of the following index.

At any given moment, the whole system is at a definite state, and therefore so is each variable; the state of each variable either is or is not a state of equilibrium for that variable (in the conditions given by the other variables). The *number of variables* that are at a state of equilibrium will be represented by i . If the whole is of n variables then obviously i must lie in the range of 0 to n .

If i equals n , then every variable is at a state of equilibrium in the conditions given by the others, so the whole is at a state of equilibrium (S. 6/8). If i is not equal to n , the other variables, $n - i$ in number, will change value at the next step in time. A new state of the whole will then occur, and i will have a new value. Thus, as the whole moves along a line of behaviour, i will change in value; and we can get a useful insight into the behaviour of the whole by considering how i will behave as time progresses.

13/7. The behaviour of i is strictly determinate once the system and its initial state have been given. In a set of systems, however, the behaviour of i is difficult to characterise except at the two extremes, where its behaviour is simple and clear. Comparison of what happens at the extremes will give us an insight that will be invaluable in the later chapters, for it will go a long way towards answering the fundamental problem of Chapter 11. (By establishing what happens in the two specially simple and clear cases we are following the strategy of S. 2/17.)

13/8. At one extreme is the polystable system that has been joined very richly, so that almost every variable is joined to almost every other. (Such a system's diagram of immediate effects would show that almost all of the $n(n - 1)$ arrows were present.) Let us consider the case in which, as in S. 12/15, every subsystem has a high probability p of being at a state of equilibrium, and in which the probabilities are all independent. How will i behave? (Here we want to know what will usually happen; what *can* happen is of little interest.)

The probability of each part being at a state of equilibrium is p , and so, if independence (of probability) holds, the probability that the whole (of n variables) is at a state of equilibrium will be p^n (by S. 6/8). If p is not very close to 1, and n is large, this quantity will be extremely small (S. 11/4). i will usually have a value not far from np (i.e. about a fraction p of the total will be

at equilibrium at any moment). Then the line of behaviour will perform a sort of random walk around this value, the whole reaching a state of equilibrium if and only if i should chance on the extreme value of n . Thus we get essentially the same picture as we got in S. 11/3: a system whose lines of behaviour are long and complex, and whose chance of reaching an equilibrium in a fairly short time is, if n is large, extremely small. In this case the time taken by the whole to arrive at a state of equilibrium will be extremely long, like T_1 of S. 11/5.

13/9. Particularly worth noting is what happens if i should happen to be large but not quite equal to n . Suppose, for instance, i were 999 in a 1,000-variable system of the type now being considered. The whole is now near to equilibrium, but what will happen? One variable is not at equilibrium and will change. As the system is richly connected, most of the 999 other variables will, at the next instant (or step), find themselves in changed conditions; whether the state each is at is *now* equilibrium will depend on factors such that (by hypothesis) 999 p will still be equilibrium, and thus i is likely to drop back simply to its average value. Thus the richly-joined form of the polystable system, even if it should get very near to equilibrium (in the sense that most of its parts are so) will be unable to retain this nearness but will almost certainly fall back to an average state. Such a system is thus typically unable to retain partial or local successes.

13/10. With the number n still large, and the probabilities p still independent, contrast the behaviour of the previous section (in which the system was assumed to be richly or completely joined) with that of the polystable system in which the primary joins between variables are scanty. (A similar system also occurs if p is made very near to 1; for, by S. 12/17, as most of the variables will be at states of equilibrium, and thus constant for most of the time, the functional connexions will also be scanty.) How will i behave in this case, especially as the scantiness approaches its limit?

Consider the case in which the scantiness has actually reached its limit. The system is now identical with one of n variables that has no connexions between any of them; it is a 'system' only in the nominal sense. In it, any part that comes to a state

of equilibrium must remain there, for no disturbance can come to it. So if two states of the whole, earlier and later, are compared, all parts contributing to i in the earlier will contribute in the later; so *the value of i cannot fall with time*. It will, of course, usually increase. Thus, this type of system goes to its final state of equilibrium progressively. Its progression, in fact, is like that of Case 3 of S. 11/5; for the final equilibrium has only to wait for the part that takes longest. The time that the whole takes will therefore be like T_3 , and thus not excessively long.

13/11. The two types of polystable system are at opposite poles, and systems in the real world will seldom be found to correspond precisely with either. Nevertheless, the two types are important by the strategy of S. 2/17, for they provide clear-cut types with clear-cut properties; if a real system is similar to either, we may legitimately argue that its properties will approximate to those of the nearer.

Polystable systems midway between the two will show a somewhat confused picture. Subsystems will be formed (e.g. as in S. 12/17) with kaleidoscopic variety and will persist only for short times; some will hold stable for a brief interval, only to be changed and to disintegrate as delimitable subsystems. The number of variables stable, i , will keep tending to climb up, as a few subsystems hold stable, only to fall back by a larger or smaller amount as they become unstable. Oscillations will be large, until one swing happens to land i at the value n , where it will stick.

More interesting to us will be the systems nearer the limit of disconnexion, when i 's tendency to increase cumulatively is better marked, so that i , although oscillating somewhat and often slipping back a little, shows a recognisable tendency to move to the value n . This is the sort of system that, after the experimenter has seen i repeatedly return to n after displacement, is apt to make him feel that i is 'trying' to get to n .

13/12. So far we have discussed only the first case of S. 12/15; what if the polystable system were composed of parts that all had their states of equilibrium characterised by a threshold? This question will specially interest the neurophysiologist, though it will be of less interest to those who are intending to work with adapting systems of other types.

The presence of threshold precludes the previous assumption of independence in the probabilities; for now a variable's chance of being at a state of equilibrium will vary in some correspondence with the values of the variable's parameters. In the case of two or more neurons, the correspondence will be one way if the effect is excitatory, and inversely if it is inhibitory. (If there is a mixture of excitatory and inhibitory modes, the outcome may be an approximation to the independent form.) To follow the subject further would lead us into more detail than is appropriate in this survey; and at the present time little can be said on the matter.

13/13. To sum up: The polystable system, if composed of parts whose states of equilibrium are distributed independently of the states of their inputs, goes to a final equilibrium in a way that depends much on the amount of functional connexion.

When the connexion is rich, the line of behaviour tends to be complex and, if n is large, exceedingly long; so the whole tends to take an exceedingly long time to come to equilibrium. When the line meets a state at which an unusually large number of the variables are stable, it cannot retain the excess over the average.

When the connexion is poor (either by few primary joins or by many constancies in the parts), the line of behaviour tends to be short, so that the whole arrives at a state of equilibrium soon. When the line meets a state at which an unusually large number of the variables are stable, it tends to retain the excess for a time, and thus to progress to total equilibrium by an accumulation of local equilibria.

Dispersion

13/14. The polystable system shows another property that deserves special notice.

Take a portion of any line of behaviour of such a system. On it we can notice, for every variable, whether it did or did not change value along the given portion. Thus, in Figure 12/18/1, in the portion indicated by the letters *B* and *C* both y and z change but x does not. In the portion indicated by *F*, x and z change but y does not. By **dispersion** I shall refer to the fact that the active variables (y and z) in the first portion are not identical with those (x and z) of the second. (In the example the portions

come from the same line, but the two portions may also come from different lines.) As the example shows, it is not implied that the two sets shall contain no common element, only that the two sets are not identical.

The importance of dispersion will be indicated in S. 13/17. Here we should notice the essential feature: though the two portions may start from points that differ only in one, or a few, variables (as in S. 12/3) the changes that result may distribute the activations (S. 12/18) to different sets of variables, i.e. to different places in the system. Thus, the important phenomenon of different *patterns* (or *values*) at one place leading to activations in different *places* in the system demands no special mechanism: any polystable system tends to show it.

13/15. If the two places are to have minimal overlap, and if the system is not to be specially designed for the separation of particular patterns of input, then all that is necessary is that the parts should have almost all their states equilibrium. Then the number active will be few; if the fraction of the total number is usually about r , and if the active variables are distributed independently, the fraction that will be common to the two sets (i.e. the overlap) will be about r^2 . This quantity can be as small as one pleases by a sufficient reduction in the value of r , which can be done by making the parts such that the proportion of states equilibrium is almost 1. Thus the polystable system may respond, to two different input states, with two responses on two sets of variables that have only small overlap.

13/16. It will be proposed later that dispersion is used widely in the nervous system. First we should notice that it is used widely in the sense-organs.

The fact that the sense-organs are not identical enforces an initial dispersion. Thus if a beam of radiation of wave-length 0.5μ is directed to the face, the eye will be stimulated but not the skin; so the optic nerve will be excited but not the trigeminal. But if the wave-length is increased beyond 0.8μ , the excitation changes from the optic nerve to the trigeminal. Dispersion has occurred because a change in the stimulus has moved the excitation (activity) from one set of anatomical elements (variables) to another.

In the skin are histologically-distinguishable receptors sensitive to touch, pain, heat, and cold. If a needle on the skin is changed from lightly touching it to piercing it, the excitation is shifted from the 'touch' to the 'pain' type of receptor; i.e. dispersion occurs.

Whether a change in colour of a stimulating light changes the excitation from one set of elements in the retina to another is at present uncertain. But dispersion clearly occurs when the light changes its position in space; for, if the eyeball does not move, the excitation is changed from one set of elements to another. The lens is, in fact, a device for ensuring that dispersion occurs: from the primitive light-spot of a Protozoan dispersion cannot occur.

It will be seen therefore that a considerable amount of dispersion is enforced before the effects of stimuli reach the central nervous system: the different stimuli not only arrive at the central nervous system different in their qualities but they often arrive by different paths, and excite different groups of cells.

13/17. The sense organs evidently have as an important function the achievement of dispersion. That it occurs or is maintained in the nervous system is supported by two pieces of evidence.

The fact that neuron processes frequently show threshold, and the fact that this property implies that the functioning elements will often be constant (S. 12/15) suggest that dispersion is *bound* to occur, by S. 12/16.

More direct evidence is provided by the fact that, in such cases as are known, the tracts from sense-organ to cortex at least maintain such dispersion as has occurred in the sense organ. The point-to-point representation of the retina on the visual cortex, for instance, ensures that the dispersion achieved in the retina will at least not be lost. Similarly the point-to-point representation now known to be made by the projection of the auditory nerve on the temporal cortex ensures that the dispersion due to pitch will also not be lost. There are therefore good reasons for believing that dispersion plays an important part in the nervous system.

Localisation in the polystable system

13/18. How will responses to a stimulus be localised in a polystable system?—how will the set of the active variables be distributed over the whole set?

In such a system, the reaction to a given stimulus, from a given state, will be regular and reproducible, for the whole is state-determined. To this extent its behaviour is lawful. But when the observer notices *which* variables have shown the activity it will probably seem lawless, for the details of where the activation spreads to have been determined by the sampling process, and the activated variables will probably be scattered over the system apparently haphazardly (subject to S. 13/4). Thus the question 'Is the reaction localised?' is ambiguous, for two different answers can be given. In the sense that the activity is restricted to certain variables of the whole system, the answer is 'yes'; but in the sense that these variables occur in no simply describable way, the answer is 'no'.

An illustration that may be helpful is given by the distribution over a town of the chimneys that 'smoke' (suffer from a forced down-draught) when the wind blows from a particular direction. The smoking or not of a particular chimney will be locally determinate; for a wind of a particular force and direction, striking the adjacent roofs at a particular angle, will regularly produce the same eddies, which will determine the smoking or not of the chimney. But geographically the smoking chimneys are not distributed with any simple regularity; for if a plan of the town is marked with a black dot for every chimney that smokes in an east wind, and a red dot for every one that smokes in a west wind, the black and red dots will probably be mixed irregularly. The phenomenon of 'smoking' is thus determined in detail yet distributed geographically at random.

13/19. Such is the 'localisation' shown by a polystable system. In so far as the brain, and especially the cerebral cortex, corresponds to the polystable, we may expect it to show 'localisation' of the same type. On this hypothesis we would expect the brain to behave as follows.

The events in the environment will provide a continuous stream of information which will pour through the sense organs into the

nervous system. The set of variables activated at one moment will usually differ from the set activated at a later moment; and the activity will spread and wander with as little apparent orderliness as the drops of rain that run, joining and separating, down a window-pane. But though the wanderings seem disorderly, the whole is reproducible and state-determined; so that if the same reaction is started again later, the same initial stimuli will meet the same local details, will develop into the same patterns, which will interact with the later stimuli as they did before, and the behaviour will consequently proceed as it did before.

This type of system would be affected by removals of material in a way not unlike that demonstrated by many workers on the cerebral cortex. The works of Pavlov and of Lashley are typical. Pavlov established various conditioned responses in dogs, removed various parts of the cerebral cortex, and observed the effects on the conditioned responses. Lashley taught rats to run through mazes and to jump to marked holes, and observed the effects of similar operations on their learned habits. The results were complicated, but certain general tendencies showed clearly. Operations involving a sensory organ or a part of the nervous system first traversed by the incoming impulses are usually severely destructive to reactions that use that sensory organ. Thus, a conditioned response to the sound of a bell is usually abolished by destruction of the cochleae, by section of the auditory nerves, or by ablation of the temporal lobes. Equally, reactions involving some type of motor activity are apt to be severely upset if the centre for this type of motor activity is damaged. But removal of cerebral cortex from other parts of the brain gave vague results. Removal of almost any part caused some disturbance, no matter from where it was removed or what type of response or habit was being tested; and no part could be found whose removal would destroy the response or habit specifically.

These results have offered great difficulties to many theories of cerebral mechanisms, but are not incompatible with the theory put forward here. For in a large polystable system the whole reaction will be based on activations that are both numerous and widely scattered. And, while any exact statement would have to be carefully qualified, we can see that, just as England's paper-making industry is not to be stopped by the devastation of any single county, so a reaction based on numerous and widely

scattered elements will tend to have more immunity to localised injury than one whose elements are few and compact.

13/20. Lashley had noticed this possibility in 1929, remarking that the memory-traces might be localised individually without conflicting with the main facts, provided there were many traces and that they were scattered widely over the cerebral cortex, and unified functionally but not anatomically. He did not, however, develop the possibility further; and the reason is not far to seek when one considers its implications.

Such a localisation would, of course, be untidy; but mere untidiness as such matters little. Thus, in a car factory the spare parts might be kept so that rear lamps were stored next to radiators, and ash-trays next to grease guns; but the lack of obvious order would not matter if in some way every item could be produced when wanted. More serious in the cortex are the effects of adding a second reaction; for merely random dispersion provides no means for relating their locations. It not only allows related reactions to activate widely separated variables, but it has no means of keeping unrelated reactions apart; it even allows them to use common variables. We cannot assume that unrelated reactions will always differ sufficiently in their sensory forms to ensure that the resulting activations stay always apart, for two stimuli may be unrelated yet closely similar. Nor is the differentiation trivial, for it includes the problem of deciding whether a few vertical stripes in a jungle belong to some reeds or to a tiger.

Not only does random dispersion lead to the intermingling of subsystems, with abundant chances of random interaction and confusion, but even more confusion is added with every fresh act of learning. Even if some order has been established among the previous reactions, each addition of a new reaction is preceded by a period of random trial and error which will necessarily cause the changing of step-mechanisms which were already adjusted to previous reactions, which will be thereby upset. At first sight, then, such a system might well seem doomed to fall into chaos. Nevertheless, I hope to show, from S. 15/4 on, that there are good reasons for believing that its tendency will actually be towards ever-increasing adaptation.