

CHAPTER 9

Ultrastability in the Living Organism

9/1. The principle of ultrastability has so far been treated as a principle in its own right, true or false without reference to possible applications. This separation has prevented the possibility of a circular argument; but the time for its application has now come. I propose, therefore, the thesis that the living organism uses the principle of ultrastability as an automatic means of ensuring the adaptiveness of its learned behaviour. At first I shall cite only facts in its favour, leaving all major criticisms to Chapter 11. We shall have, of course, to assume that the animal, and particularly the nervous system, contains the necessary variables behaving as step-functions: whether this assumption is reasonable will be discussed in the next chapter.

Examples of adaptive, learned behaviour are so multitudinous that it will be quite impossible for me to discuss, or even to mention, the majority of them. I can only select a few as typical and leave the reader to make the necessary modifications in other cases.

The best introduction is not an example of learned behaviour, but Jennings' classic description of the reactions of *Stentor*, a single-celled pond animalcule. I shall quote him at length:

'Let us now examine the behaviour [of *Stentor*] under conditions which are harmless when acting for a short time, but which, when continued, do interfere with the normal functions. Such conditions may be produced by bringing a large quantity of fine particles, such as India ink or carmine, by means of a capillary pipette, into the water currents which are carried to the disc of *Stentor*.

'Under these conditions the normal movements are at first not changed. The particles of carmine are taken into the pouch and into the mouth, whence they pass into the internal protoplasm. If the cloud of particles is very dense,

or if it is accompanied by a slight chemical stimulus, as is usually the case with carmine grains, this behaviour lasts but a short time; then a definite reaction supervenes. The animal bends to one side . . . It thus as a rule avoids the cloud of particles, unless the latter is very large. This simple method of reaction turns out to be more effective in getting rid of stimuli of all sorts than might be expected. If the first reaction is not successful, it is usually repeated one or more times . . .

'If the repeated turning toward one side does not relieve the animal, so that the particles of carmine continue to come in a dense cloud, another reaction is tried. The ciliary movement is suddenly reversed in direction, so that the particles against the disc and in the pouch are thrown off. The water current is driven away from the disc instead of toward it. This lasts but an instant, then the current is continued in the usual way. If the particles continue to come, the reversal is repeated two or three times in rapid succession. If this fails to relieve the organism, the next reaction—contraction—usually supervenes.

'Sometimes the reversal of the current takes place before the turning away described first; but usually the two reactions are tried in the order we have given.

'If the *Stentor* does not get rid of the stimulation in either of the ways just described, it contracts into its tube. In this way it of course escapes the stimulation completely, but at the expense of suspending its activity and losing all opportunity to obtain food. The animal usually remains in the tube about half a minute, then extends. When its body has reached about two-thirds its original length, the ciliary disc begins to unfold and the cilia to act, causing currents of water to reach the disc, as before.

'We have now reached a specially interesting place in the experiment. Suppose that the water currents again bring the carmine grains. The stimulus and all the external conditions are the same as they were at the beginning. Will the *Stentor* behave as it did at the beginning? Will it at first not react, then bend to one side, then reverse the current, then contract, passing anew through the whole series of reactions? Or shall we find that it has become changed by the experiences it has passed through, so that it will now contract again into its tube as soon as stimulated?

'We find the latter to be the case. As soon as the carmine again reaches its disc, it at once contracts again. This may be repeated many times, as often as the particles come to the disc, for ten or fifteen minutes. Now the animal after each contraction stays a little longer in the tube than it did at first. Finally it ceases to extend, but contracts

repeatedly and violently while still enclosed in its tube. In this way the attachment of its foot to the object on which it is situated is broken and the animal is free. Now it leaves its tube and swims away. In leaving the tube it may swim forward out of the anterior end of the tube; but if this brings it into the region of the cloud of carmine, it often forces its way backwards through the substance of the tube, and thus gains the outside. Here it swims away, to form a new tube elsewhere.

‘... the changes in behaviour may be summed up as follows:

- (1) No reaction at first; the organism continues its normal activities for a time.
- (2) Then a slight reaction by turning into a new position.
- (3) ... a momentary reversal of the ciliary current ...
- (4) ... the animal breaks off its normal activity completely by contracting strongly ...
- (5) ... it abandons its tube ...’

The behaviour of *Stentor* bears a close resemblance to the behaviour of an ultrastable system. The physical correspondences necessary would be as follows:—*Stentor* and its environment constitute an absolute system by S. 3/9; for Jennings, having set the carmine flowing, interferes no further. They consequently correspond to the whole ultrastable system, which is also absolute by the definition of S. 8/4. The observable (here: visible) variables of *Stentor* and its environment correspond to the main variables of the ultrastable system. In *Stentor* are assumed to be variables which behave like, and correspond to, the step-functions of the ultrastable system. The critical states of the organism’s step-functions surround the region of the normal values of the organism’s essential variables so that its step-functions change value if the essential variables diverge widely from their usual, normal values. These critical states must be nearer to the normal value than the extreme limits of the essential variables, for these critical states must be reached before the essential variables reach the extreme limits compatible with life.

Now compare the behaviour of the ultrastable system, described in S. 8/7, with the behaviour of organisms like *Stentor*, epitomised by Jennings in these words:

‘Anything injurious to the organism causes changes in its behaviour. These changes subject the organism to new

conditions. As long as the injurious condition continues, the changes of behaviour continue. The first change of behaviour may not be regulatory [what I call 'adaptive'], nor the second, nor the third, nor the tenth. But if the changes continue, subjecting the organism successively to all possible different conditions, a condition will finally be reached that relieves the organism from the injurious action, provided such a condition exists. Thereupon the changes in behaviour cease and the organism remains in the favourable situation.'

The resemblance between my statement and his is obvious. Jennings grasped the fundamental fact that *aimless* change can lead to adaptation provided that some active process rejects the bad and retains the good. He did not, however, give any physical (i.e. non-vital) reason why this selection should occur. He records only that it does occur, and that its occurrence is sufficient to account for adaptation at the primitive level.

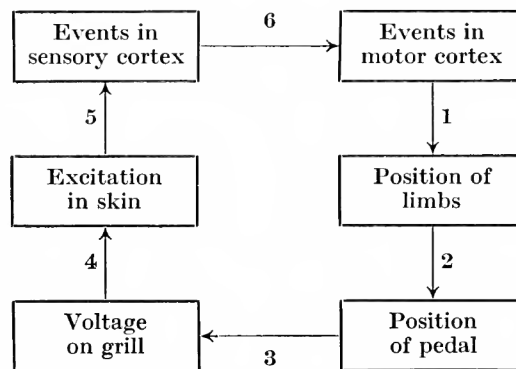
The first example therefore suggests that, provided we are willing to assume that *Stentor* contains step-functions which (a) affect *Stentor's* behaviour, and (b) have critical states that are encountered before the essential variables reach their extreme limits, *Stentor* may well achieve its final adaptation by using the automatic process of ultrastability.

9/2. The next example includes more complicating factors but the main features are clear. Mowrer put a rat into a box with a gridded metal floor. The grill could be electrified so as to give shocks to the rat's paws. Inside the box was a pedal which, if depressed, at once stopped the shocks.

When a rat was put into the box and the electric stimulation started, the rat would produce various undirected activities such as jumping, running, squealing, biting at the grill, and random thrashing about. Sooner or later it would depress the pedal and stop the shocks. After the tenth trial, the application of the shock would usually cause the rat to go straight to the pedal and depress it. These, briefly, are the observed facts.

Consider the internal linkages in this system. We can sufficiently specify what is happening by using six variables, or sets of variables: those shown in the box-diagram below. By considering the known actions of part on part in the real system we can construct the diagram of immediate effects. Thus, the

excitations in the motor cortex certainly control the rat's bodily movements, and such excitations have no direct effect on any of the other five groups of variables; so we can insert arrow 1, and know that no other arrow leaves that box. (The single arrow, of course, represents a complex channel.) Similarly, the other arrows of the diagram can be inserted. Some of the arrows, e.g. 2 and 4, represent a linkage in which there is not



a positive physical action all the time; but here, in accordance with S. 2/3, we regard them as permanently linked though sometimes acting at zero degree.

Having completed the diagram, we notice that it forms a functional circuit. The system is complete and isolated, and may therefore be treated as absolute. To apply our thesis, we assume that the cerebral part, represented by the boxes around arrow 6, contains step-functions whose critical states will be transgressed if stimuli of more than physiological intensity are sent to the brain.

We now regard the system as straightforwardly ultrastable, and predict what its behaviour must be. It is started, by hypothesis, from an initial state at which the voltage is high. This being so, the excitation at the skin and in the brain will be high. At first the pattern of impulses sent to the muscles does not cause that pedal movement which would lower the voltage on the grill. These high excitations in the brain will cause some step-functions to change value, thus causing different patterns of body movement to occur. The step-functions act directly only at stage 6, but changes there will (S. 14/11) affect the field

of all six groups of main variables. These changes of field will continue to occur as long as the high excitation in the brain persists. They will cease when, and only when, the linkages at stage 6 transform an excitation of skin receptors into such a bodily movement as will cause, through the pedal, a reduction in the excitation of the skin receptors; for only such linkages can stop further encounters with critical states. The system that is, will change until there occurs a stable field. The stability will be shown by an increase in the voltage on the grill leading to changes through skin, brain, muscles, and pedal that have the effect of *opposing* the increase in voltage. The stability, in addition, has the property that it keeps the essential variables within physiological limits; for by it the rat is protected from electrical injury, and the nervous system from exhaustion.

It will be noted that although action 3 has no direct connection, either visually in the real apparatus or functionally in the diagram of immediate effects, with the site of the changes at 6, yet the latter become adapted to the nature of the action at 3. The subject was discussed in S. 5/15.

This example shows, therefore, that if the rat and its environment formed an ultrastable system and acted purely automatically, they would have gone through the same changes as were observed by Mowrer.

9/3. The two examples have taken a known fact of animal behaviour and shown its resemblance to the behaviour of the ultrastable system. Equally, the behaviour of the homeostat, a system known to be ultrastable, shows some resemblance to that of a rudimentary nervous system. The tracings of Figures 8/8/4 and 8/8/5 show its elementary power of adaptation. In Figure 8/8/5 the reversal at R_1 might be regarded as the action of an experimenter who changed the conditions so that the 'aim' (stability and homeostasis) could be achieved only if the 'organism' (Unit 1) reversed its action. Such a reversal might be forced on a rat who, having learned a maze whose right fork led to food, was transferred to a maze where food was to be found only down the left fork. The homeostat, as Figure 8/8/5 shows, develops a reversed action in Unit 1, and this reversal may be compared with the reversal which is usually found to occur in the rat's behaviour.

A more elaborate reaction by the homostat is shown in Figure 9/3/1.

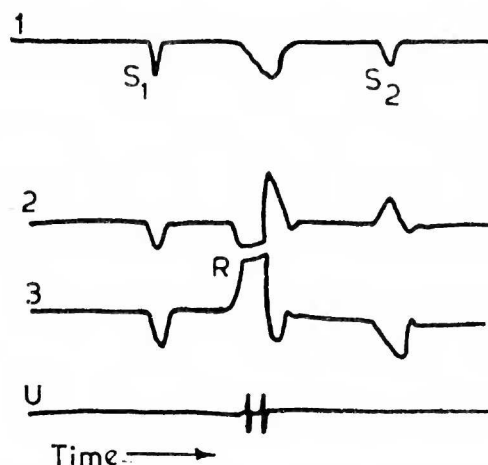
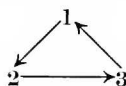


FIGURE 9/3/1: Three units interacting. At R the effect of 2 on 3 was reversed in polarity.

The machine was arranged so that its diagram of immediate effects was



The effect $3 \rightarrow 1$ was set permanently so that a movement of 3 made 1 move in the opposite direction. The action $1 \rightarrow 2$ was unselector-controlled, and $2 \rightarrow 3$ hand-controlled. When the tracing commenced, the actions $1 \rightarrow 2$ and $2 \rightarrow 3$ were demonstrated by the downward movement, forced by the operator, of 1 at S_1 : 2 followed 1 downward (similar movement), and 3 followed 2 downward (similar movement). 3 then forced 1 upward, opposed the original movement, and produced stability.

At R , the hand-control ($2 \rightarrow 3$) was reversed, so that 2 now forced 3 to move in the *opposite* direction to itself. This change set up a vicious circle and destroyed the stability; but unselector changes occurred until the stability was restored. A forced downward movement of 1, at S_2 , demonstrated the regained stability.

The tracing, however, deserves closer study. The action $2 \rightarrow 3$ was reversed at R , and the responses of 2 and 3 at S_2 demonstrate this reversal; for while at S_1 they moved similarly, at S_2 they moved oppositely. Again, a comparison of the uniselector-controlled action $1 \rightarrow 2$ before and after R shows that whereas beforehand 2 moved similarly to 1, afterwards it moved oppositely. The reversal in $2 \rightarrow 3$, caused by the operator, thus evoked a reversal in $1 \rightarrow 2$ controlled by the uniselector. The second reversal is compensatory to the first.

The nervous system provides many illustrations of such a series of events: first the established reaction, then an alteration made in the environment by the experimenter, and finally a reorganisation within the nervous system, compensating for the experimental alteration. The homeostat can thus show, in elementary form, this power of self-reorganisation.

The necessity of ultrastability

9/4. In the previous sections a few simple examples have suggested that the adaptation of the living organism may be due to ultrastability. But the argument has not excluded the possibility that other theories might fit the facts equally well. I shall now give, therefore, evidence to show that ultrastability is not merely plausible but necessary: the organism *must* be ultrastable.

First the primary assumptions: they are such as few scientists would doubt. It is assumed that the organism and its environment form an absolute system, and that the organism sometimes changes from one regular way of behaving to another. The crucial question is whether we can prove that the organism's mechanism must contain step-functions. In S. 22/5 is given such a proof, stated in mathematical form; but its theme is simple and can be stated in plain words.

Suppose a 'machine' or experiment behaves regularly in one way, and then suddenly changes to behaving in another way, again regularly. Suppose, for instance, a pharmacologist, testing the effect of a new drug on the frog's heart, finds at every test all through one day that it causes the pulse-rate to lessen. Next morning, taking records of the effect, he finds at every

attempt that it causes the pulse-rate to increase. He will almost certainly ask himself 'What has changed?'

Such facts provide valid evidence that some variable has changed value. I need not elaborate the logic for no experimenter would question it. What has been sometimes overlooked though, is that we are also entitled to draw the deduction that the variable, being as it is an effective factor towards the system, must, throughout the previous day, have remained constant; for otherwise the reactions observed during the day could not have been regular. For the same reason, it must also have been constant throughout the next morning. And further, the two constant values cannot have been equal, for then the hearts' behaviours would not have been changed. Assembling these inferences, we deduce that the variable must have behaved as a step-function. Exactly the same argument, applied to the changes of behaviour shown by Jennings' *Stentor*, leads to the deduction that within the organism there must have been variables behaving as step-functions.

Is there any escape from this conclusion? It rests primarily on the simple thesis that a determinate system does not, if started from identical states, do one thing on one day and something else on another day. There seems to be no escape if we assume that the systems we are discussing are determinate. Suppose, then, that we abandon the assumption of determinism and allow indeterminism of atomic type to affect heart, *Stentor*, or brain to an observable extent. This would allow us to explain the 'causeless' overnight change; but then we would be unable to explain the regularity throughout the previous day and the next morning. It seems there is no escape that way. Again, we could, with a little ingenuity, construct a hypothesis that the pharmacologist's experiment was affected by a small group of variables, whose joint action produced the observed result but not one of which was a step-function; and it might be claimed that the theorem had been shown false. But this is really no exception, for we are not concerned with what variables 'are' but with how they behave, and in particular with how they behave towards the system in question. If a group of variables behaves towards the system as a step-function, then it *is* a step-function; for the 'step-function' is defined primarily as a form of behaviour, not as a thing.

Once it is agreed that a system, such as that of Mowrer's rat, contains step-functions, then all it needs is that they should not be few for the system to be admitted as ultrastable.

After this, we can examine the qualifications that were added when considering *Stentor* as an ultrastable system. Are they, too, necessary? Not with the assumptions made so far in this section, but they become so if we add the postulates that the system 'adapts' in the sense of S. 5/8, and that it does so by 'trial and error'. In order to be definite about what 'trial and error' implies, here is the concept defined explicitly:

- (1) The organism makes trials only when 'dissatisfied' or 'irritated' in some way.
- (2) Each trial persists for a finite time.
- (3) While the irritation continues, the succession of trials continues.
- (4) The succeeding trial is not specially related to the preceding, nor better than it, but only different.
- (5) The process stops at the first trial that relieves the irritation.

The argument goes thus. As each step-function forms part of an absolute system, its change must depend on its own and on the other variables' values; there must, therefore, be certain states—the critical—at which it changes value. When, in the process of adaptation by trial and error, the step-function changes value, its critical states must have been encountered; and since, by (1) above, the step-functions change value only when the organism is 'dissatisfied' or 'irritated', the critical states must be so related to the essential variables that only when the organism is driven from its normal physiological state does its representative point encounter the critical states. This knowledge is sufficient to place the critical states in the functional sense: they must have values intermediate between those of the normal state and those of the essential variables' limits. The qualifications introduced in S. 9/1 are thus necessary.

Training

9/5. The process of 'training' will now be shown in its relation to ultrastability.

All training involves some use of 'punishment' or 'reward', and we must translate these concepts into our form. 'Punish-

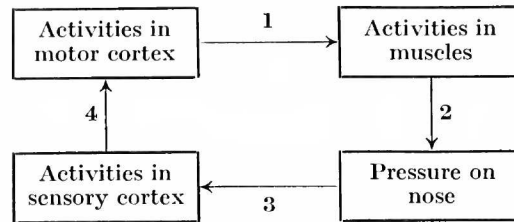
ment' is simple, for it means that some sensory organs or nerve endings have been stimulated with an intensity high enough to cause step-function changes in the nervous system (S. 7/6 and 10/2). The concept of 'reward' is more complex. It usually involves the supplying of some substance (e.g. food) or condition (e.g. escape) whose absence would act as 'punishment'. The chief difficulty is that the evidence suggests that the nervous system, especially the mammalian, contains intricate and specialised mechanisms which give the animals properties not to be deduced from basic principles alone. Thus it has been shown that dogs with an oesophageal fistula, deprived of water for some hours, would, when offered water, drink approximately the quantity that would correct the deprivation, and would then stop drinking; they would stop although no water had entered stomach or system. The properties of these mechanisms have not yet been fully elucidated; so training by reward uses mechanisms of unknown properties. Here we shall ignore these complications. We shall assume that the training is by pain, i.e. by some change which threatens to drive the essential variables outside their normal limits; and we shall assume that training by reward is not essentially dissimilar.

It will now be shown that the process of 'training' necessarily implies the existence of feedback. But first the functional relationship of the experimenter to the experiment must be made clear.

The experimenter often plays a dual role. He first plans the experiment, deciding what rules shall be obeyed during it. Then, when these have been fixed, he takes part in the experiment and obeys these rules. With the first role we are not concerned. In the second, however, it is important to note that the experimenter is now *within* the functional machinery of the experiment. The truth of this statement can be appreciated more readily if his place is taken by an untrained but obedient assistant who carries out the instructions blindly; or better still if his place is taken by an apparatus which carries out the prescribed actions automatically.

When the whole training is arranged to occur automatically the feedback is readily demonstrated if we construct the diagram of immediate effects. Thus, a pike in an aquarium was separated from some minnows by a sheet of glass; every time he dashed

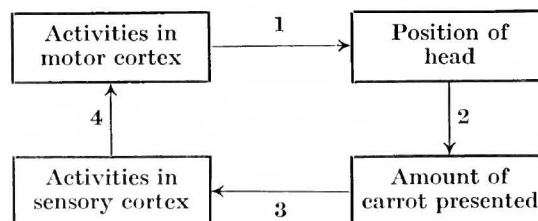
at the minnows he struck the glass. The following immediate effects can be clearly distinguished :



The arrow 1 represents the control exerted through spinal cord and motor nerves. Effect 2 is discontinuous but none the less clear : the experiment implies that some activities led to a high pressure on the nose while others led to a zero pressure. Effects 3 and 4 are the simple neuro-physiological results of pressures on the nose.

Although the diagram has some freedom in the selection of variables for naming, the system, regarded as a whole, clearly has feedback.

In other training experiments, the regularity of action 2 (supplied above by the constant physical properties of glass) may be supplied by an assistant who constantly obeys the rules laid down by the experimenter. Grindley, for instance, kept a guinea-pig in a silent room in which a buzzer was sounded from time to time. If and only if its head turned to the right did a tray swing out and present it with a piece of carrot ; after a few nibbles the carrot was withdrawn and the process repeated. Feedback is demonstrably present in this system, for the diagram of immediate effects is :

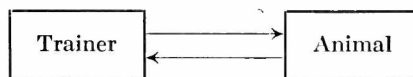


The buzzer, omitted for clarity, comes in as parameter and serves merely to call this dynamic system into functional existence ; for only when the buzzer sounds does the linkage 2 exist.

This type of experiment reveals its essential dynamic structure more clearly if contrasted with elementary Pavlovian conditioning. In the experiments of Grindley and Pavlov, both use the sequences '... buzzer, animal's response, food...' In Grindley's experiment, the value of the variable 'food' *depended on the animal's response*: if the head turned to the left, 'food' was 'no carrot', while if the head turned to the right, 'food' was 'carrot given'. But in Pavlov's experiments the nature of every stimulus throughout the session was already determined *before the session commenced*. The Pavlovian experiment, therefore, allows no effect from the variable 'animal's behaviour' to 'quantity of food given'; there is no functional circuit and no feedback.

It may be thought that the distinction (which corresponds to that made by Hilgard and Marquis between 'conditioning' and 'instrumental learning') is purely verbal. This is not so, for the description given above shows that the distinction may be made objectively by examining the structure of the experiment. Cullen *et al.* performed an experiment in which feedback, at first absent, was added at an intermediate stage: as a result, the dog's behaviour changed. They gave the dog a shock to the leg and sounded a tone. The reaction to the shock was one of generalised struggling movements of the body and retraction of the leg. After a few sessions the tone produced generalised struggling and retraction of the leg. So far there had been no feedback; but now the conditions were changed: the shock was given at the tone only if the foot was not raised. As a result the dog's behaviour changed: the response rapidly narrowed to a simple and precise flexion of the leg.

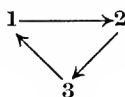
It will be seen, therefore, that the 'training' situation necessarily implies that the trainer, or some similar device, is an integral part of the whole system, which has feedback:



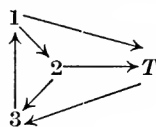
We shall now suppose this system to be ultrastable, and we shall trace its behaviour on this supposition. The step-functions are, of course, assumed to be confined to the animal; both because the human trainer may be replaced in some experiments

by a device as simple as a sheet of glass (in the example of the pike); and because the rules of the training are to be decided in advance (as when we decide to punish a house-dog whenever he jumps into a chair), and therefore to be invariant throughout the process. Suppose then that jumping into a chair always results in the dog's sensory receptors being excessively stimulated. As an ultrastable system, step-function values which lead to jumps into chairs will be followed by stimulations likely to cause them to change value. But on the occurrence of a set of step-function values leading to a remaining on the ground, excessive stimulation will not occur, and the values will remain. (The cessation of punishment when the right action occurs is no less important in training than its administration after the wrong action.)

The process can be shown on the homeostat. Figure 9/5/1 provides an example. Three units were joined:



and to this system was joined a 'trainer', actually myself, which acted on the rule that if the homeostat did not respond to a forced movement of 1 by an *opposite* movement of 2, then the trainer would force 3 over to an extreme position. The diagram of immediate effects is therefore really



Part of the system's feedbacks, it will be noticed, pass through T .

At S_1 , 1 was moved and 2 moved similarly. This is the 'forbidden' response; so at D_1 , 3 was forced by the trainer to an extreme position. Step-functions changed value. At S_2 , the homeostat was tested again: again it produced the forbidden response; so at D_2 , 3 was again forced to an extreme position. At S_3 , the homeostat was tested again: it moved in the desired way, so no further deviation was forced on 3. And at S_4 and S_5 the homeostat continued to show the desired reaction.

From S_1 onwards, T 's behaviour is determinate at every instant ; so the system composed of 1, 2, 3, T , and the uniselectors, is absolute.

Another property of the whole system should be noticed. When the movement-combination '1 and 2 moving similarly' occurs, T is thereby impelled, under the rules of the experiment, to force 3 outside the region bounded by the critical states. Of any inanimate system which behaved in this way we would

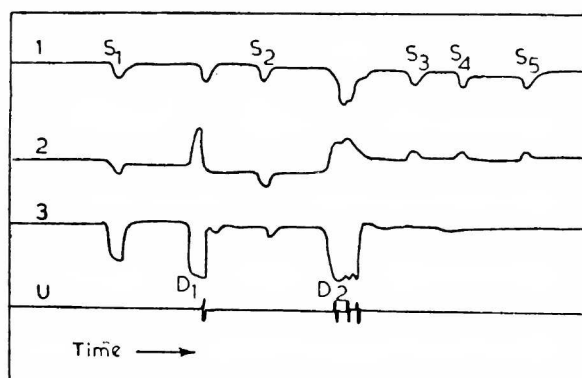


FIGURE 9/5/1: Three units interacting. The downstrokes at S are forced by the operator. If 2 responds with a downstroke, the trainer drives 3 past its critical surface.

say, simply, that the line of behaviour from the state at which 1 and 2 started moving was unstable. So, to say in psychological terms that the 'trainer' has 'punished' the 'animal' is equivalent to saying in our terms that the system has a set of step-function values that make it unstable.

In general, then, we may identify the behaviour of the animal in 'training' with that of the ultrastable system adapting to another system of fixed characteristics.

9/6. A remarkable property of the nervous system is its ability to adapt itself to surgical alterations of the bodily structure. From the first work of Marina to the recent work of Sperry, such experiments have aroused interest and no little surprise.

Over thirty years ago, Marina severed the attachments of the internal and external recti muscles of a monkey's eyeball and re-attached them in crossed position so that a contraction of

the external rectus would cause the eyeball to turn not outwards but inwards. When the wound had healed, he was surprised to discover that the two eyeballs still moved together, so that binocular vision was preserved.

More recently Sperry severed the nerves supplying the flexor and extensor muscles in the arm of the spider monkey, and re-joined them in crossed position. After the nerves had regenerated, the animal's arm movements were at first grossly inco-ordinated but improved until an essentially normal mode of progression was re-established. The two examples are typical of a great number of experiments, and will suffice for the discussion.

In S. 3/12 it was decided that the anatomical criterion for dividing the system into 'animal' and 'environment' is not the only possible: a functional criterion is also possible. Suppose a monkey, to get food from a box, has to pull a lever towards itself; if we sever the flexor and extensor muscles of the arm and re-attach them in crossed position then, so far as the cerebral cortex is concerned, the change is not essentially different from that of dismantling the box and re-assembling it so that the lever has to be pushed instead of pulled. Spinal cord, peripheral nerves, muscles, bones, lever, and box—all are 'environment' to the cerebral cortex. A reversal in the cerebral cortex will compensate for a reversal in its environment whether in spinal cord, muscles, or lever. It seems reasonable, therefore, to expect that the cerebral cortex will use the same compensatory process whatever the site of reversal.

I have already shown, in S. 8/10 and in Figure 8/10/1, that the ultrastable system arrives at a stability in which the values of the step-functions are related to those of the parameters of the system, i.e. to the surrounding fixed conditions, and that the relation will be achieved whether the parameters have values which are 'normal' or are experimentally altered from those values. If these conclusions are applied to the experiments of Marina and Sperry, the facts receive an explanation, at least in outline. To apply the principle of ultrastability we must add an assumption that 'binocular vision' and 'normal progression' have neural correlates such that deviations from binocular vision or from normal progression cause an excitation sufficient to cause changes of step-function in those cerebral mechanisms that determine the actions. (The plausibility of this assumption will

be discussed in S. 9/8.) Ultrastability will then automatically lead to the emergence of behaviour which produces binocular vision or normal progression. For this to be produced, the step-function values must make appropriate allowance for the particular characteristics of the environment, whether 'crossed' or 'uncrossed'. S. 8/10 and Figure 9/3/1 showed that an ultrastable system will make such allowance. The adaptation shown by Marina's monkey is therefore homologous with that shown by Mowrer's rat, for the same principle is responsible for both.

9/7. 'Learning' and 'memory' are vast subjects, and any theory of their mechanisms cannot be accepted until it has been tested against all the facts. It is not my intention to propose any such theory, since this work confines itself to the problem of adaptation. Nevertheless I must indicate briefly the relation of this work to the two concepts.

'Learning' and 'memory' have been given almost as many definitions as there are authors to write of them. The concepts involve a number of aspects whose interrelations are by no means clear; but the theme is that a past experience has caused some change in the organism's behaviour, so that this behaviour is different from what it would have been if the experience had not occurred. But such a change of behaviour is also shown by a motor-car after an accident; so most psychologists have insisted that the two concepts should be restricted to those cases in which the later behaviour is better adapted than the earlier.

The ultrastable system shows in its behaviour something of these elementary features of 'learning'. In Figure 9/3/1, for instance, the pattern of behaviour produced at S_2 is different from the pattern at S_1 . The change has occurred after the 'experience' of the instability at R . And the new field produced by the step-function change is better adapted than the previous field, for an unstable field has been replaced by a stable.

An elementary feature of 'memory' is also shown; for further responses, S_3 , S_4 , etc. would repeat S_2 's pattern of behaviour, and thereby might be said to show a 'memory' of the reversal at R ; for the later pattern is adapted to the reversal at R , and not adapted to the original setting.

The ultrastable system, then, shows rudimentary 'learning' and 'memory'. The subject is resumed in S. 11/3.

The control of aim

9/8. The ultrastable systems discussed so far, though developing a variety of fields, have sought a constant goal. The homeostat sought central positions and the rat sought zero grill-potential. In this section will be described some methods by which the goal may be varied.

If the critical states' distribution in the main-variables' phase-space is altered by any means whatever, the ultrastable system

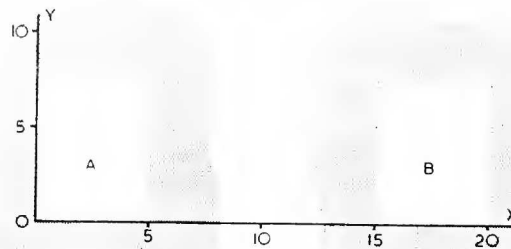


FIGURE 9/8/1.

will be altered in the goal it seeks. For the ultrastable system will always develop a field which keeps the representative point within the region of the critical states (S. 8/7). Thus if (Figure 9/8/1) for some reason the critical states moved to surround *B* instead of *A*, then the terminal field would change from one which kept *x* between 0 and 5 to one which kept *x* between 15 and 20.

A related method is illustrated by Figure 9/8/2. An ultrastable system *U* interacts with a variable *A*. *E* and *R* represent the immediate effects which *U* and *A* have on each other; they may be thought of as *A*'s effectors and receptors. If *A* should have a marked effect on the ultrastable system, the latter will, of course, develop a field stabilising *A*; at what value will depend markedly on the action of *R*. Suppose, for instance, that *U* has its critical states all at values 0 and 10, so that it always selects a field stabilising all its main variables between these values. If *R* is such that, if *A* has some value *a*, *R* transmits to *U* the value $5a - 20$, then it is easy to see that *U* will develop a field holding *A* within one unit of the value 5; for if the field makes

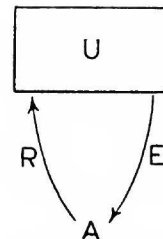


FIGURE 9/8/2.

holding *A* within one unit of the value 5; for if the field makes

A go outside the range 4 to 6, it will make U go outside the range 0 to 10, and this will destroy the field. So U becomes '5-seeking'. If the action of R is now changed to transmitting, not $5a - 20$ but $5a + 5$, then U will change fields until it holds A within one unit of 0; and U is now '0-seeking'. So anything that controls the b in $R = 5a + b$ controls the 'goal' sought by U .

As a more practical example, suppose U is mobile and is ultrastable, with its critical states set so that it seeks situations of high illumination; such would occur if its critical states resembled, in Figure 9/8/1, B rather than A . Suppose too that R is a ray of light. If in the path of R we place a red colour-filter, then green light will count as 'no light' and the system will actively seek the red places and avoid the green. If now we merely replace the red filter by a green, the whole aim of its movements will be altered, for it will now seek the green places and avoid the red.

Next, suppose R is a transducer that converts a temperature at A into an illumination which it transmits to U . If R is arranged so that a high temperature at A is converted into a high illumination, then U will become actively goal-seeking for hot places. And if the relation within R is reversed, U will seek for cold places. Clearly, whatever controls R controls U 's goal.

There is therefore in general no difficulty in accounting for the fact that a system may seek one goal at one time and another goal at another time.

Sometimes the change, of critical states or of the transducer R , may be under the control of a single parameter. When this happens we must distinguish two complexities. Suppose the parameter can take only two values and the system U is very complicated. Then the system is simple in the sense that it will seek one of only two goals, and is complicated in the sense that the behaviour with which it gets to the goal is complicated. That the behaviour is complicated is no proof, or even suggestion, that the parameter's relations to the system must be complicated; for, as was shown in S. 6/3, the number of fields is equal to the number of values the parameter can take, and has nothing to do with the number of main variables. It is this latter that determines, in general, the complexity of the goal-seeking behaviour.

These considerations may clarify the relations between the change of concentration of a sex-hormone in the blood of a mammal and its consequent sexual goal-seeking behaviour. A simple alternation between 'present' and 'absent', or between two levels with a threshold, would be sufficient to account for any degree of complexity in the two behaviours, for the complexity is not to be related to the hormone-parameter but to the nervous system that is affected by it. Since the mammalian nervous system is extremely complex, and since it is, at almost every point, sensitive to both physical and chemical influences, there seems to be no reason to suppose that the directiveness of the sex-hormones on the brain's behaviour is essentially different from that of any parameter on the system it controls. (That the sex-hormones evoke specifically sexual behaviour is, of course, explicable by the fact that evolution, through natural selection, has constructed specific mechanisms that react to the hormone in the specific way.)

Ultrastability and the gene-pattern

9/9. In S. 1/9 it was pointed out that although the power of adaptation shown by a species ultimately depends on its genetic endowment, yet the number of genes is, in the higher animals, quite insufficient to specify every detail of the final neuronic organisation. It was suggested that in the higher animals, the genes must establish function-rules which will look after the details automatically.

As the minimal function-rules have now been provided (S. 8/7) it is of interest to examine the specification of the ultrastable system to see how many items will have to be specified genetically if the ovum is to grow into an ultrastable organism. The items are as follows:

- (1) The animal and its environment must form an absolute system (S. 3/9);
- (2) The system must be actively dynamic;
- (3) Essential variables must be defined for the species (S. 3/14);
- (4) Step-functions are to be provided (S. 8/4);
- (5) Their critical states are all to be similar (S. 8/6);
- (6) The critical states are to be related in value to the limiting values of the essential variables (S. 9/1).

From these basic rules, an ultrastable system of any size can be generated by mere repetition of parts. Thus each critical state is to have a value related to the limits of the essential variables; but this requirement applies to all other critical states by mere repetition. The repetition needs fewer genes than would be necessary for independent specification.

It is not possible to give an exact estimate of the number of genes necessary to determine the development of an ultrastable system. But the number of items listed above is only six; and though the number of genes required is probably a larger number, it may well be less than the number known to be available. It seems, therefore, that the requirement of S. 1/9 has been met satisfactorily.

9/10. If the higher animals are made ultrastable by their genetic inheritance, the gene-pattern must have been shaped by natural selection. Could an ultrastable system be developed by natural selection?

Suppose the original organism had no step-functions; such an organism would have a permanent, invariable set of reactions. If a mutation should lead to the formation of a single step-function whose critical states were such that, when the organism became distressed, it changed value *before* the essential variables transgressed their limits, and if the step-function affected in any way the reaction between the organism and the environment, then such a step-function might increase the organism's chance of survival. A single mutation causing a single step-function might therefore prove advantageous; and this advantage, though slight, might be sufficient to establish the mutation as a species characteristic. Then a second mutation might continue the process. The change from the original system to the ultrastable can therefore be made by a long series of small changes, each of which improves the chance of survival. The change is thus possible under the action of natural selection.

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