CHAPTER 3

The Animal as Machine

3/1. WE shall assume at once that the living organism in its nature and processes is not essentially different from other matter. The truth of the assumption will not be discussed. The chapter will therefore deal only with the technique of applying this assumption to the complexities of biological systems.

The numerical specification of behaviour

3/2. If the method laid down in the previous chapter is to be followed, we must first determine to what extent the behaviour of an organism is capable of being specified by *variables*, remembering that our ultimate test is whether the representation can be by dial readings (S. 2/3).

There can be little doubt that any single quantity observable in the living organism can be treated at least in principle as a variable. All bodily movements can be specified by co-ordinates. All joint movements can be specified by angles. Muscle tensions can be specified by their pull in dynes. Muscle movements can be specified by co-ordinates based on the bony structure or on some fixed external point, and can therefore be recorded numerically. A gland can be specified in its activity by its rate of secretion. Pulse-rate, blood-pressure, temperature, rate of blood-flow, tension of smooth muscle, and a host of other variables can be similarly recorded.

In the nervous system our attempts to observe, measure, and record have met great technical difficulties. Nevertheless, much has been achieved. The action potential, the essential event in the activity of the nervous system, can now be measured and recorded. The excitatory and inhibitory states of the centres are at the moment not directly recordable, but there is no reason to suppose that they will never become so.

3/3. Few would deny that the elementary physico-chemical events in the living organism can be treated as variables. But some may hesitate before accepting that readings on dials are adequate for the description of *all* significant biological events. As the remainder of the book will assume that they are sufficient, I must show how the various complexities of biological experience can be reduced to this standard form.

A simple case which may be mentioned first occurs when an event is recorded in the form ' strychnine was injected at this moment ', or ' a light was switched on ', or ' an electric shock was administered '. Such a statement treats only the positive event as having existence and ignores the other state as a nullity. It can readily be converted to a numerical form suitable for our purpose by using the device mentioned in S. 2/3. Such events would then be recorded by assuming, in the first case, that the animal always had strychnine in its tissues but that at first the quantity present was 0 mg. per g. tissue ; in the second case, that the light was always on, but that at first it shone with a brightness of 0 candlepower ; and in the last case, that an electric potential was applied throughout but that at first it had a value of 0 volts. Such a method of description cannot be wrong in these cases for it defines exactly the same set of objective facts. Its advantage from our point of view is that it provides a method which can be used uniformly over a wide range of phenomena : the variable is always present, merely varying in value.

But this device does not remove all difficulties. It sometimes happens in physiology and psychology that a variable seems to have no numerical counter-part. Thus in one experiment two cards, one black and one brown, were shown alternately to an animal as stimuli. One variable would thus be ' colour ' and it would have two values. The simplest way to specify colour numerically is to give the wave-length of its light ; but this method cannot be used here, for ' black ' means ' no light ', and ' brown ' does not occur in the spectrum. Another example would occur if an electric heater were regularly used and if its switch indicated only the degrees ' high ', ' medium ', and ' low '. Another example is given on many types of electric apparatus by a pilot light which, as a variable, takes only the two values ' lit ' and ' unlit '. More complex examples occur frequently in psychological experiments. Table 2/5/1, for instance, contains a variable ' part of skin stimulated ' which, in Pavlov's table, takes only two values: ' usual place ' and ' new place '. Even more complicated variables are common in Pavlov's experiments. Many a table contains a variable ' stimulus ' which takes such values as ' bubbling water ', ' metronome ', ' flashing light '. A similar difficulty occurs when an experimenter tests an animal's response to injections of toxins, so that there will be a variable ' type of toxin ' which may take the two values ' Diphtheria type Gravis ' and ' Diphtheria type Medius '. And finally the change may involve an extensive re-organisation of the whole experimental situation. Such would occur if the experimenter, wanting to test the effect of the general surroundings, tried the effect of the variable ' situation of the experiment ' by giving it alternately the two values ' in the animal house ' and ' in the open air '. Can such variables be represented by number ?

In some of the examples, the variables might possibly be specified numerically by a more or less elaborate specification of their physical nature. Thus ' part of skin stimulated ' might be specified by reference to some system of co-ordinates marked on the skin ; and the three intensities of the electric heater might be specified by the three values of the watts consumed. But this method is hardly possible in the remainder of the cases ; nor is it necessary. For numbers can be used cardinally as well as ordinally, that is, they may be used as mere labels without any reference to their natural order. Such are the numberings of the divisions of an army, and of the subscribers on a telephone system; for the subscriber whose number is, say, 4051 has no particular relation to the subscriber whose number is 4052 : the number identifies him but does not relate him.

It may be shown (S. 21/1) that if a variable takes a few values which stand in no simple relation to one another, then each value may be allotted an arbitrary number ; and provided that the numbers are used systematically throughout the experiment, and that their use is confined to the experiment, then no confusion can arise. Thus the variable ' situation of the experiment ' might be allotted the arbitrary value of ' 1 ' if the experiment occurs in the animal house, and ' 2 ' if it occurs in the open air.

Although ' situation of the experiment ' involves a great number of physical variables, the aggregate may justifiably be treated as a single variable provided the arrangement of the experiment is such that the many variables are used throughout as one aggregate which can take either of two forms. If, however, the aggregate were split in the experiment, as would happen if we recorded four classes of results:

(1) in the animal house in summer
(2) in the animal house in winter
(3) in the open air in summer
(4) in the open air in winter

then we must either allow the variable ‘ condition of experiment ’ to take four values, or we could consider the experiment as subject to two variables: ‘ site of experiment ’ and ‘ season of year ’, each of which takes two values. According to this method, what is important is not the material structure of the technical devices but the experiment’s logical structure.

3/4. But is the method yet adequate? Can all the living organisms’ more subtle qualities be numericised in this way? On this subject there has been much dispute, but we can avoid a part of the controversy; for here we are concerned only with certain qualities defined.

First, we shall be dealing not so much with qualities as with behaviour: we shall be dealing, not with what an organism feels or thinks, but with what it does. The omission of all subjective aspects (S. 1/11) removes from the discussion the most subtle of the qualities, while the restriction to overt behaviour makes the specification by variable usually easy. Secondly, when the non-mathematical reader thinks that there are some complex quantities that cannot be adequately represented by number, he is apt to think of their representation by a single variable. The use of many variables, however, enables systems of considerable complexity to be treated. Thus a complex system like ‘ the weather over England ’, which cannot be treated adequately by a single variable, can, by the use of many variables, be treated as adequately as we please.

3/5. To illustrate the method for specifying the behaviour of a system by variables, two examples will be given. They are of little intrinsic interest; more important is the fact that they demonstrate that the method is exact and that it can be extended to any extent without loss of precision.

The first example is from a physiological experiment. A dog was subjected to a steady loss of blood at the rate of one per cent of its body weight per minute. Recorded are the three variables :

(x) rate of blood-flow through the inferior vena cava,
(y) ,, ,, ,, ,, ,, muscles of a leg,
(z) ,, ,, ,, ,, ,, gut.

The changes of the variables with time are shown in Figure 3/5/1. It will be seen that the changes of the variables show a characteristic pattern, for the blood-flow through leg and gut falls more than that through the inferior vena cava, and this difference is characteristic of the body's reaction to haemorrhage. The use

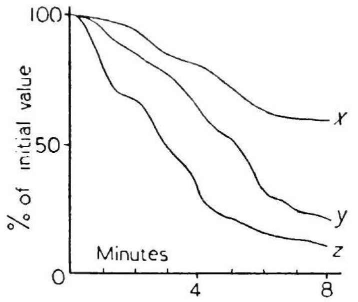

FIGURE 3/5/1 : Effect of haemorrhage on the rate of blood-flow through : x, the inferior vena cava ; y, the muscles of a leg ; and z, the gut. (From Rein.)

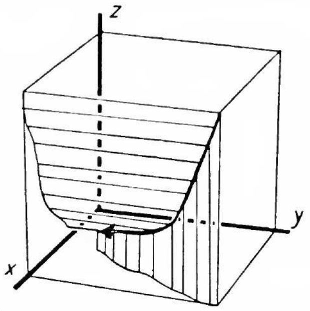

FIGURE 3/5/2 : Phase-space and line of behaviour of the data shown in Figure 3/5/1.

of more than one variable has enabled the *pattern* of the reaction to be displayed.

The changes specify a line of behaviour, shown in Figure 3/5/2. Had the line of behaviour pointed in a different direction, the change would have corresponded to a change in the pattern of the body's reaction to haemorrhage.

The second example uses certain angles measured from a cinematographic record of the activities of a man. His body moved forward but was vertical throughout. The four variables are :

(w) angle between the right thigh and the vertical
(x) ,, ,, ,, left ,, ,, ,, ,,
(y) ,, ,, ,, right ,, ,, ,, right tibia
(z) ,, ,, ,, left ,, ,, ,, left ,,

In w and x the angle is counted positively when the knee comes forward: in y and z the angles are measured behind the knee. The line of behaviour is specified in Table 3/5/1. The reader can easily identify this well-known activity.

		Time (seconds)								
		0	0·1	0·2	0·3	0·4	0·5	0·6	0·7	0·8
Variable	w	45	10	−10	−20	−35	0	60	70	45
	x	−35	0	60	70	45	10	−10	−20	−35
	y	170	180	180	160	120	80	60	100	170
	z	120	80	60	100	170	180	180	160	120

TABLE 3/5/1.

The organism as system

3/6. In a physiological experiment the nervous system is usually considered to be absolute. That it can be made absolute is assumed by every physiologist before the work starts, for he assumes that it is subject to the fundamental assumption of S. 2/15: that if every detail within it could be determined, its subsequent behaviour would also be determined. Many of the specialised techniques such as anaesthesia, spinal transection, root section, and the immobilisation of body and head in clamps are used to ensure proper isolation of the system—a necessary condition for its absoluteness (S. 2/15). So unless there are special reasons to the contrary, the nervous system in a physiological experiment has the properties of an absolute system.

3/7. Similarly it is usually agreed that an animal undergoing experiments on its conditioned reflexes is a physico-chemical system such that if we knew every detail we could predict its behaviour. Pavlov's insistence on complete isolation was intended to ensure that this was so. So unless there are special reasons to the contrary, the animal in an experiment with conditioned reflexes has the properties of an absolute system.

The environment

3/8. These two examples, however, are mentioned only as introduction; rather we shall be concerned with the nature of the free-living organism within a natural environment.

Given an organism, its **environment** is defined as *those variables whose changes affect the organism, and those variables which are changed by the organism's behaviour*. It is thus defined in a purely functional, not a material, sense. It will be treated uniformly with our treatment of all variables: we assume it is representable by dials, is explorable (by the experimenter) by primary operations, and is intrinsically determinate.

Organism and environment

3/9. The theme of the chapter can now be stated: the free-living organism and its environment, taken together, form an absolute system.

The concepts developed in the previous sections now enable us to treat both organism and environment by identical methods, for the same primary assumptions are made about each. The two parts act and re-act on one another (S. 3/11), and are therefore properly regarded as two parts of one system. And since we have assumed that the conjoint system is state-determined, we may treat the whole as absolute.

3/10. As example, that the organism and its environment form a single absolute system, consider (in so far as the activities of balancing are concerned) a bicycle and its rider in normal progression.

First, the forward movement may be eliminated as irrelevant, for we could study the properties of this dynamic system equally well if the wheels were on some backward-moving band. The variables can be identified by considering what happens. Suppose the rider pulls his right hand backwards: it will change the angular position of the front wheel (taking the line of the frame as reference). The changed angle of the front wheel will start the two points, at which the wheels make contact with the ground, moving to the right. (The physical reasons for this movement are irrelevant: the fact that the relation is determined is sufficient.)

The rider's centre of gravity being at first unmoved, the line vertically downwards from his centre of gravity will strike the ground more and more to the left of the line joining the two points. As a result he will start to fall to the left. This fall will excite nerve-endings in the organs of balance in the ear, impulses will pass to the nervous system, and will be switched through it, if he is a trained rider, by such a route that they, or the effects set up by them, will excite to activity those muscles which push the *right* hand forwards.

We can now specify the variables which must compose the system if it is to be absolute. We must include: the angular position of the handlebar, the velocity of lateral movement of the two points of contact between wheels and road, the distance laterally between the line joining these points and the point vertically below the rider's centre of gravity, and the angular deviation of the rider from the vertical. These four variables are defined by S. 3/8 to be the 'environment' of the rider. (Whether the fourth variable is allotted to 'rider' or to 'environment' is optional (S. 3/12)). To make the system absolute, there must be added the variables of the nervous system, of the relevant muscles, and of the bone and joint positions.

As a second example, consider a butterfly and a bird in the air, the bird chasing the butterfly, and the butterfly evading the bird. Both use the air around them. Every movement of the bird stimulates the butterfly's eye and this stimulation, acting through the butterfly's nervous system, will cause changes in the butterfly's wing movements. These movements act on the enveloping air and cause changes in the butterfly's position. A change of position immediately changes the excitations in the bird's eye, and this leads through its nervous system to changed movements of the bird's wings. These act on the air and change the bird's position. So the processes go on. The bird has as environment the air and the butterfly, while the butterfly has the bird and the air. The whole may justifiably be assumed absolute.

3/11. The organism affects the environment, and the environment affects the organism: such a system is said to have 'feedback' (S. 4/12).

The examples of the previous section provide illustration. The rider's arm moves the handlebars, causing changes in the environment; and changes in these variables will, through the rider's sensory receptors, cause changes in his brain and muscles. When bird and butterfly manoeuvre in the air, each manoeuvre of one causes reactive changes to occur in the other.

The same feature is shown by the example of S. 1/12—the type problem of the kitten and the fire. The various stimuli from the fire, working through the nervous system, evoke some reaction from the kitten's muscles; equally the kitten's movements, by altering the position of its body in relation to the fire, will cause changes to occur in the pattern of stimuli which falls on the kitten's sense-organs. The receptors therefore affect the muscles (by effects transmitted through the nervous system), and the muscles affect the receptors (by effects transmitted through the environment). The action is two-way and the system possesses feedback.

The observation is not new:—

> 'In most cases the change which induces a reaction is brought about by the organism's own movements. These cause a change in the relation of the organism to the environment: to these changes the organism reacts. The whole behaviour of free-moving organisms is based on the principle that it is the movements of the organism that have brought about stimulation.'
>
> (Jennings.)

> 'The good player of a quick ball game, the surgeon conducting an operation, the physician arriving at a clinical decision—in each case there is the flow from signals interpreted to action carried out, back to further signals and on again to more action, up to the culminating point of the achievement of the task'.
>
> (Bartlett.)

> 'Organism and environment form a whole and must be viewed as such.'
>
> (Starling.)

It is necessary to point to the existence of feedback in the relation between the free-living organism and its environment because most physiological experiments are deliberately arranged to avoid feedback. Thus, in an experiment with spinal reflexes, a stimulus is applied and the resulting movement recorded; but the movement is not allowed to influence the nature or duration of the stimulus. The action between stimulus and movement is therefore one-way. A similar absence of feedback is enforced in the Pavlovian experiments with conditioned reflexes: the stimulus may evoke salivation, but the salivation has no effect on the nature or duration of the stimulus.

Such an absence of feedback is, of course, useful or even essential in the analytic study of the behaviour of a mechanism, whether animate or inanimate. But its usefulness in the laboratory should not obscure the fact that the free-living animal is not subject to these constraints.

Sometimes systems which seem at first sight to be one-way prove on closer examination to have feedback. Walking on a smooth pavement, for instance, seems to involve so little reference to the structures outside the body that the nervous system might seem to be producing its actions without reference to their effects. *Tabes dorsalis*, however, prevents incoming sensory impulses from reaching the brain while leaving the outgoing motor impulses unaffected. If walking were due simply to the outgoing motor impulses, the disease would cause no disturbance to walking. In fact, it upsets the action severely, and demonstrates that the incoming sensory impulses are really playing an essential, though hidden, part in the normal action.

Sometimes the feedback can be demonstrated only with difficulty. Thus, Lloyd Morgan raised some ducklings in an incubator.

> 'The ducklings thoroughly enjoyed a dip. Each morning, at nine o'clock, a large black tray was placed in their pen, and on it a flat tin containing water. To this they eagerly ran, drinking and washing in it. On the sixth morning the tray and tin were given them in the usual way, but without any water. They ran to it, scooped at the bottom and made all the motions of the beak as if drinking. They squatted in it, dipping their heads, and waggling their tails as usual. For some ten minutes they continued to wash in non-existent water . . .'

Their behaviour might suggest that the stimuli of tray and tin were compelling the production of certain activities and that the results of these activities were having no back-effect. But further experiment showed that some effect was occurring:

> 'The next day the experiment was repeated with the dry tin. Again they ran to it, shovelling along the bottom with their beaks, and squatting down in it. But they soon gave up. On the third morning they waddled up to the dry tin, and departed.'

Their behaviour at first suggested that there was no feedback. But on the third day their change of behaviour showed that, in fact, the change in the bath had had some effect on them.

The importance of feedback lies in the fact that systems which possess it have certain properties (S. 4/14) which cannot be shown by systems lacking it. Systems with feedback cannot adequately be treated as if they were of one-way action, for the feedback introduces properties which can be explained only by reference to the properties of the particular feedback used. (On the other hand a one-way system can, without error, be treated as if it contained feedback: we assume that one of the two actions is present but at zero degree (S. 2/3). In other words, systems without feedback are a sub-class of the class of systems with feedback.)

3/12. As the organism and its environment are to be treated as a single system, the dividing line between 'organism' and 'environment' becomes partly conceptual, and to that extent arbitrary. Anatomically and physically, of course, there is a unique and obvious distinction between the two parts of the system; but if we view the system functionally, ignoring purely anatomical facts as irrelevant, the division of the system into 'organism' and 'environment' becomes vague. Thus, if a mechanic with an artificial arm is trying to repair an engine, then the arm may be regarded either as part of the organism that is struggling with the engine, or as part of the machinery with which the man is struggling.

Once this flexibility of division is admitted, almost no bounds can be put to its application. The chisel in a sculptor's hand can be regarded either as a part of the complex biophysical mechanism that is shaping the marble, or it can be regarded as a part of the material which the nervous system is attempting to control. The bones in the sculptor's arm can be regarded either as part of the organism or as part of the 'environment' of the nervous system. Variables within the body may justifiably be regarded as the 'environment' of some other part. A child has to learn not only how to grasp a piece of bread, but how to chew without biting his own tongue; functionally both bread and tongue are part of the environment of the cerebral cortex. But the environments with which the cortex has to deal are sometimes even deeper in the body than the tongue : the child has to learn how to play without exhausting itself utterly, and how to talk without getting out of breath.

These remarks are not intended to confuse, but to show that later arguments (S. 17/4 and Chapter 18) are not unreasonable. There it is intended to treat one group of neurons in the cerebral cortex as the environment of another group. These divisions, though arbitrary, are justifiable because we shall always treat the system as a whole, dividing it into parts in this unusual way merely for verbal convenience in description.

It should be noticed that from now on ' the system ' means not the nervous system but the whole complex of the organism and its environment. Thus, if it should be shown that ' the system ' has some property, it must not be assumed that this property is attributed to the nervous system : it belongs to the whole ; and detailed examination may be necessary to ascertain the contributions of the separate parts.

3/13. In some cases the dynamic nature of the interaction between organism and environment can be made intuitively more obvious by using the device, common in physics, of regarding the animal as the centre of reference. In locomotion the animal would then be thought of as pulling the world past itself. Provided we are concerned only with the relation between these two, and are not considering their relations to any third and independent body, the device will not lead to error. It was used in the ' rider and bicycle ' example.

By the use of animal-centred co-ordinates we can see that the animal has much more control over its environment than might at first seem possible. Thus when a dog puts its foot on a sharp and unmovable stone, the latter does not seem particularly dynamic. Yet the dog can cause great changes in this environment—by moving its foot away. Again, while a frog cannot change air into water, a frog on the bank of a stream can, with one small jump, change its world from one ruled by the laws of mechanics to one ruled by the laws of hydrodynamics.

Static systems (like the sharp stone) can always be treated as if dynamic (though not conversely), for we have only to use the device of S. 2/3 and treat the static variable as one which is undergoing change of zero degree. *The dynamic view is therefore* *the more general.* For this reason the environment will always be treated as wholly dynamic.

Essential variables

3/14. The biologist must view the brain, not as being the seat of the 'mind', nor as something that 'thinks', but, like every other organ in the body, as a specialised means to survival. We shall use the concept of 'survival' repeatedly; but before we can use it, we must, by S. 2/8, transform it to our standard form. What does it mean in terms of primary operations?

Physico-chemical systems may undergo the most extensive transformations without showing any change obviously equivalent to death, for matter and energy are indestructible. Yet the distinction between a live horse and a dead one is obvious enough —they fetch quite different prices in the market. The distinction must be capable of objective definition.

It is suggested that the definition may be obtained in the following way. That an animal should remain 'alive' certain variables must remain within certain 'physiological' limits. What these variables are, and what the limits, are fixed when we have named the species we are working with. In practice one does not experiment on animals in general, one experiments on one of a particular species. In each species the many physiological variables differ widely in their relevance to survival. Thus, if a man's hair is shortened from 4 inches to 1 inch, the change is trivial; if his systolic blood-pressure drops from 120 mm. of mercury to 30, the change will quickly be fatal.

Every species has a number of variables which are closely related to survival and which are closely linked dynamically so that marked changes in any one leads sooner or later to marked changes in the others. Thus, if we find in a rat that the pulse-rate has dropped to zero, we can predict that the respiration rate will soon become zero, that the body temperature will soon fall to room temperature, and that the number of bacteria in the tissues will soon rise from almost zero to a very high number. These important and closely linked variables will be referred to as the **essential** variables of the animal.

How are we to discover them, considering that we may not use borrowed knowledge but must find them by the method of

S. 2/8? There is no difficulty. Given a species, we observe what follows when members of the species are started from a variety of initial states. We shall find that large initial changes in some variables are followed in the system by merely transient deviations, while large initial changes in others are followed by deviations that become ever greater till the 'machine' changes to something very different from what it was originally. The results of these primary operations will thus distinguish, quite objectively, the essential variables from the others. This distinction may not be quite clear, for an animal's variables cannot be divided sharply into 'essential' and 'not essential'; but exactness is not necessary here. All that is required is the ability to arrange the animal's variables in an approximate order of importance. Inexactness of the order is not serious, for nowhere will we use a particular order as a basis for particular deductions.

We can now define 'survival' objectively and in terms of a field: it occurs when a line of behaviour takes no essential variable outside given limits.

References

BARTLETT, F. C. The measurement of human skill. *British Medical Journal*, **1**, 835; 14 June 1947.

JENNINGS, H. S. *Behavior of the lower organisms.* New York, 1906.

MORGAN, C. LLOYD. *Habit and instinct.* London, 1896.

REIN, H. Die physiologischen Grundlagen des Kreislaufkollapses. *Archiv für klinische Chirurgie*, **189**, 302; 1937.

STARLING, E. H. *Principles of human physiology.* London, 6th edition, 1933.