III.—THE NERVOUS SYSTEM AS PHYSICAL MACHINE: WITH SPECIAL REFERENCE TO THE ORIGIN OF ADAPTIVE BEHAVIOUR.

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§ 1. *Introduction.*

A century's study of the nervous system has shown that one of its main functions is that it brings the organism into adaptation with the environment. The adaptation is of two types: (1) There are fixed, inborn mechanisms, the reflexes, which are necessarily adapted by natural selection. But with these we are not concerned in this paper. (2) In addition to the reflexes, however, there are formed in each organism during its life a large number of adaptive reactions which are not inborn but which have to be developed in each individual according to the environment. The fact that " a burned child dreads the fire " exemplifies this second type. There is no need to stress its wide occurrence nor its importance.

The author has been concerned for some years with attempting to reconcile the fact of the occurrence of this type of adaptation with the usual hypothesis that the brain is a machine, *i.e.*, a physico-chemical system. In the opinion of some, there is a fundamental impossibility that any isolated machine could show behaviour of this type; but the impossibility has not been clearly proved. It seemed possible, however, that a more elaborate study of the essentials of " machines " might show possibilities hitherto overlooked.

Working in this direction the author was led to examine in minute detail, *i.e.*, mathematically, exactly what is meant by a " machine ", and later to study the peculiar events which occur when a machine " breaks ". Having discovered and established a mathematical and rigorous theory of the subject, he found that one of its first applications was to give a straightforward account of the *physical* origin of adaptive behaviour.

The paper is divided into three parts : The first (§§ 1 and 2) clarifies the problem and gets it clearly stated. The second part (§§ 3-6) is concerned with the fundamental properties of machines. In the third part (§ 7) is given the application to living organisms, showing how the theorems given in the second part solve the problem.

§ 2. *The problem.*

Before we can proceed we must change the form of the problem. Physics, and mathematics, know nothing of "adaptation" as such ; so we must first convert our biological problem into its equivalent physical form. We therefore re-examine it from the physical point of view so that we know what *physical* features to look for.

With regard to the nervous system, it is treated here as a purely physico-chemical system, of dynamic type. We use the concepts that parts of it (the "receptors") are affected by the environment, that actions and interactions occur in the nervous system, and that some parts (the "effectors") act on the environment.

What of the "adaptive behaviour" ? The meaning of "behaviour" is clear enough, but what of "adaptive" ? When we examine an adaptive reaction, we find certain striking features, features which any physical theory is bound to explain :

(1) The development of the reaction involves, presumably, the development in the nervous system of some special arrangement or *organisation* (in a general sense) to mediate it, no single neuron being able to produce the result.
(2) This organisation is of neurons and has the remarkable property that the neurons develop the *right* organisation and not one of the almost infinite number of possible wrong ones.
(3) The neuronic activities in this organisation are observed to be *co-ordinated* so that they form a coherent whole.

Our problem may be provisionally stated by saying that we wish to find whether any machine-like system can produce these results—or if not we should like to *prove* it impossible.

But so far we have given no physical meaning to the "right" result, nor to "adapted" behaviour. It will now be suggested that an organism which is "adapted" to its environment is equivalent to a machine in a state of equilibrium. (We must be careful here to distinguish between (1) the state where the animal is already adapted to the environment and (2) the process by which that final state is achieved. The word "adaptation" is often used to cover both. In this section we shall discuss the characteristics of an animal which has already reached that state. The question of how it was arrived at will be the subject of the subsequent sections).

First, an animal " adapted " to its environment is, above all, self-preserving. This means, on closer examination, that it does not starve, nor die of thirst, nor injure itself, nor allow itself to be deprived of oxygen, and so on. More precisely, this means that there are certain variables such as the amount of sugar in the blood, of water in the tissues, of mechanical strains on bone and sinew, of oxygen supply to the tissues, and so on, and that an adapted animal's behaviour always ensures the maintenance of these variables at certain more or less fixed values. Thus, typical adapted behaviour would be shown by a fish which sought out food when it was hungry, or by an animal whose respiration became brisker if placed in an atmosphere deficient in oxygen. In all such cases the animal shows its adaptation by producing behaviour whose end result is to bring back these important variables after a disturbance. Pavlov (1927) states the matter with perfect clarity :

> " The animal must respond to changes in the environment in such a manner that its responsive activity is directed towards the preservation of its existence. . . . Being a definite circumscribed material system, it can only continue to exist so long as it is in continuous equilibrium with the forces external to it."

Is a state of equilibrium *sufficient* to ensure adaptation ? It is doubtful whether any other characteristic may be imposed without arbitrariness. Thus, suppose an animal does always produce behaviour which keeps its food supply constant, its water intake constant, its oxygen supply adequate, its carbon dioxide level in the blood correct, etc., have we any right to say that the behaviour, however peculiar it may seem to us, is not adapted ? When we consider the extraordinary range of types of living creatures and the great variety of ways in which they maintain themselves, it seems that, in the simpler animals at least, any active equilibrium which maintains steady the essential physiological variables must be called " adapted ".

Let us now reverse the argument, by examining a machine in equilibrium and observing to what extent it imitates adaptive behaviour. As a simple example we may take a pendulum hanging vertically. If we push the bob away from the lowest point to the right, we find that forces are set up tending to move the bob to the left. And if we push it to the left it immediately pushes to the right. And the behaviour is similar if we push or pull it to or from us. Again, consider a thermostat, as an interacting series of parts which keeps the temperature of a water bath constant. If we upset the thermostat by deliberately chilling the water, we find that changes occur in the system, the net result of which is that the water is heated more strongly. *It is an elementary property of all systems in equilibrium that they react so as to oppose disturbance.*

Space prohibits an exhaustive discussion but it may therefore be reasonably assumed (Ashby, 1940) that " adapted " behaviour is equivalent to " the behaviour of a system in equilibrium ". If this hypothesis be conceded, the problem takes the new and more definite form : *how does the nervous system develop such an organisation internally that, as a machine, it shall be in equilibrium with its environment ?*

But before this can be answered we must know more about " machine ", " organisation " and " equilibrium ". (The reader, however, is recommended to proceed direct to § 6, referring back only if the argument seems unconvincing or faulty.)

§ 3. *Machines.*

(The next four sections are required to establish the conclusions of § 7. But to proceed by stating the conclusion and then proving it would mean that an extensive mathematical system would have to be proved bit by bit in inverted order. I have preferred to develop the theory in its natural direction. When this has proceeded far enough I can then use this to tackle the original problem. The theory can be, and is being, developed in many directions. Here it will be given only so far as is required for the subject of this paper).

The words " machine " and " organisation " have a multitude of possible meanings, but here we are concerned with the idea of a number of parts which interact on one another, *e.g.*, neurons which transmit impulses to one another. Roughly, the set of parts is the machine, and the way they are put together is the organisation. (Note that we are in no way restricted to systems with Newtonian dynamics).

A typical example of a dynamic organisation is given by a frame with a number of heavy beads in it, the beads being joined together by elastic strands to form an irregular network. Such a network, if pressed out of position and then released, will move (as specified by the positions and velocities of the beads) with a pattern of movement which depends (1) on the original displacement and (2) on the constant factors such as the masses of the beads, the lengths and arrangement of the strands, the shape of the frame, etc. It is an organisation because the movement of any one bead at a given instant depends on where the other beads are at that instant, *i.e.*, it is impossible to predict the movement of one bead merely by studying that one bead.

To handle such a case we start by labelling the necessary variables $x_1, x_2, \ldots, x_n$. It is immediately necessary to appreciate that the number of variables is not the same as the number of material bodies present. Thus, if the frame above contained three beads, the number of variables would be eighteen: three co-ordinates of position and three of momentum for each bead.

A "configuration" of such a system (at a given instant of time) is the set of numerical values of the variables. The "behaviour" of such a system is defined by the successive configurations with the time-intervals between them.

It is now postulated that our system, whatever it is, must be such that each configuration determines the configuration which follows it. (This hypothesis lies at the root of most dynamic science and means that we are dealing with a determinate, and not a capricious, system). It is a *fundamental theorem* that, for a system to have this property, it is necessary and sufficient for it to be specified by equations of type:

$$\left.\begin{aligned} \frac{dx_1}{dt} &= f_1(x_1, x_2, \ldots, x_n) \\ \frac{dx_2}{dt} &= f_2(x_1, x_2, \ldots, x_n) \\ &\cdots\cdots \\ \frac{dx_n}{dt} &= f_n(x_1, x_2, \ldots, x_n) \end{aligned}\right\} \qquad (1)$$

Such a system is a *complete* system. It is specially to be noted that t and functions of t other than $x_1, x_2, \ldots, x_n$ are absent explicitly from the right-hand side. The f's must be single-valued, but no restrictions of continuity or differentiability are implied. A "machine" will now be used exclusively to mean a complete system.

As an example we may consider a pendulum swinging sideways through a finite angle x_1. To make the system complete we also need the angular velocity (x_2). The equations (in our form) are:

$$\left.\begin{aligned}\frac{dx_1}{dt} &= x_2 \\ \frac{dx_2}{dt} &= -\frac{g}{l}\sin x_1\end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (2)$$

where g is the acceleratio n of gravity and l the length.

The set of equations (1) has a unique set of solutions of form

$$x_i = F_i(x_1^0, x_2^0, \ldots, x_n^0;\ t)\ (i = 1, 2, \ldots, n) \qquad (3)$$

where

$$F_i(x_1^0, x_2^0, \ldots, x_n^0;\ 0) = x_2^0\ (i = 1, 2, \ldots, n)$$

and $x_1^0, x_2^0, \ldots, x_n^0$ is an arbitrary set of constants. These equations (3) give the observed behaviour of the system after it has been started at $t = 0$, at the configuration $x_1^0, x_2^0, \ldots, x_n^0$. In a complete system the functions F_i define a *finite continuous group*. That such a set of equations as (1) has all the ordinary properties of machines may be shown in ways too many to give here.

Following the methods usual in statistical mechanics, each configuration $x_1, x_2, \ldots, x_n$ defines a "representative point" in a geometric n-dimensional space with $x_1, x_2, \ldots, x_n$ as co-ordinates. It is a well-known theorem that equations (1) define a field of paths in this space such that if we start at a given configuration and follow the behaviour defined by (1), then the representative point will follow the path it was started on. That the field should be constant in time, it is necessary and sufficient that the system be complete. This is important since it means that only complete systems can be said to have any fixity of behaviour.

It should be noted that:

(1) Each *point* in the x-space corresponds to a single instantaneous state of the machine.

(2) Each *path* corresponds to the behaviour which follows the starting of the machine from some particular configuration.

(3) The *field* corresponds to the equations (1), and gives all the possible behaviours of that particular machine.

(These facts are illustrated by the example of the next section).

The variables are, as we said, those items which alter with the time. But behind these are the "constants", or parameters, of the system. (The two must be kept most carefully distinct in the reader's mind). If we alter a parameter the effect on equations (1) is to change the f's; and its effect on the machine is to alter the way one variable affects another. We therefore define the "organisation" of the system as corresponding to, and specified by, the f's of equations (1). Prolonged testing has convinced me that this identification is valid and fruitful. A set of equations

$$\frac{dx_i}{dt} = g_i(x_1, \ldots, x_n; \; p_1, \ldots, p_r) \; (i = 1, \ldots, n) \quad (4)$$

will therefore have as many organisations as the set $p_1, p_2, \ldots, p_r$ has values.

§ 4. *Breaks.*

Having defined " machine " and " organisation ", we now proceed to examine exactly what is meant by a machine " breaking ". To fix the ideas, suppose we have a pendulum swinging from side to side and that the string breaks so that the bob falls downwards. The first point to notice is that after the break, the result, no matter how chaotic, is still a machine, within our definition, except that it is now a different machine. Examination of other cases soon shows the first point : a break is a change of organisation.

The next point to consider is whether the changes which occur at the moment of breaking are ordinary, *i.e.*, representable by the equations of a complete system or not. It is clear that there is no question here of anything going against the fundamental laws of nature. All breaking events, whatever they are, are perfectly natural : *e.g.*, the breaking of a cord, the fusing of a wire, the snapping of a rod. *Therefore they are deducible from their immediately preceding states.* And this means that the events of the break occur within a complete system. It means that when we have a machine (like the pendulum above) and then a break, and then a second machine (the pendulum falling downwards) we can, if we like, set up more comprehensive equations which will treat the whole set of events as the ordinary events of one single machine.

This fact, that we may include a break-event in the equations of a complete system, is so important that I must give an example. It will answer much possible criticism and will illuminate the whole paper. (It has been selected to be as short as possible).

Consider a weight of mass m hanging downwards under gravity on a (massless) elastic strand. If the elastic is stretched too far it will break and the mass will fall. This provides, I think, a perfectly natural and typical example of a break.

Let the elastic pull be k dynes for each centimeter stretch from its position of rest (and assume for simplicity that the elastic expands similarly when compressed). Measure x, the position of the mass, downwards from the position of the elastic when there is no mass. The movement of the mass (vertical only) is usually written

$$\frac{d}{dt}\left(m\frac{dx}{dt}\right) = gm - kx,$$

where g is the acceleration due to gravity. This is not in our standard form but becomes so on writing $x_1 = x$, $x_2 = dx/dt$, giving

$$\left.\begin{aligned} \frac{dx_1}{dt} &= x_2 \\ \frac{dx_2}{dt} &= g - \frac{k}{m}x_1 \end{aligned}\right\}$$

If the elastic breaks, k becomes 0 and our equation becomes

$$\left.\begin{aligned} \frac{dx_1}{dt} &= x_2 \\ \frac{dx_2}{dt} &= g \end{aligned}\right\}$$

illustrating the change of organisation.

To bring in the break explicitly, suppose the elastic will stretch to a point X and then snaps. k now becomes a variable with two values, K and 0, say, whose development in time proceeds by the substitution

$$k' = \lambda(x_1, k)$$

(not written dk/dt since " dk " is finite) where k' is the value of k consequent on its having had the value k an instant before, and where λ is a functional symbol defined by

$\lambda(x_1, k)$		k: 0	k: K
x_1	< X	0	K
	> X	0	0

Examining this substitution we find, assuming x_1 starts at less than X and that k starts at K, that as long as x_1 remains less than X, k will keep the value K (*i.e.*, remain unbroken). But if x_1 once becomes larger than X, then k will go to 0 and will stay there, whatever happens subsequently. It thus describes correctly what happens to the elasticity k. So the final set of equations is

$$\left.\begin{aligned}\frac{dx_1}{dt} &= x_2 \\ \frac{dx_2}{dt} &= g - \frac{k}{m}x_1 \\ k' &= \lambda(x_1, k)\end{aligned}\right\}$$

It is obviously a complete system. The set of equations, though a little unusual in form, *does define the solutions,* thereby demonstrating the possibility of a break being specified correctly in a complete system even when the break occurs in the middle of the time covered. (In actual practice one would use some continuous approximation to the k'-substitution).

A break can therefore be considered to be an ordinary incident in the activity of one (more comprehensive) machine.

We now ask the converse question: Under what conditions is it possible to divide the activities of a machine into two parts (in time) so that we can say that there was a machine which broke and formed the second ? (We ignore the trivial case of just changing its name).

It may be shown that there is only one possible way: among the variables there must be one which stays constant for a time and then changes suddenly to a new value, also constant. In other words, one of the variables must be a step-function of the time. Thus, suppose it to be x_n, that it can take only the two values x_n^0 and x_n^1, and that it starts at x_n^0. When this is so, then as long as that particular variable stays constant we may, if we like, no longer write it explicitly, lessen the variables by one and simplify the equations

$$\frac{dx_i}{dt} = f_i(x_1, \ldots, x_{n-1}, x_n^0) \quad (i = 1, \ldots, n-1)$$

to $$\frac{dx_1}{dt} = g_i(x_1, \ldots, x_{n-1}) \quad (i = 1, \ldots, n-1)$$

where

$$g_i(x_1, \ldots, x_{n-1}) \equiv f_i(x_1, \ldots, x_{n-1}, x_n^0) \; (i = 1, \ldots, n-1).$$

And the g-equations will remain valid as long as x_n maintains its first value of x_n^0. When, however, we arrive at the time when it suddenly changes, the g's no longer represent the machine correctly, and we shall have

$$\frac{dx_i}{dt} = f_i\,(x_1 \ldots, x_{n-1}, x^1{}_n) \quad (i = 1, \ldots, n-1)$$

which will simplify to, say,

$$\frac{dx_i}{dt} = h_i(x_1, \ldots, x_{n-1}) \quad (i = 1, \ldots, n-1)$$

for the second part of the machine's activities. We may now, if we like, say that the first machine (specified by the g's) has broken and become the second (specified by the h's). This fact, that *a step-function in a complete system creates two new complete systems*, is the mathematical point of the whole paper.

(We must be careful to note the possibility of confusion over "*the* machine". If we are referring to the system which does not break, then "the machine" refers to the variables $x_1, x_2, \ldots, x_n$, but if we are using the "break" concept, then "the machine" refers to the system of $n - 1$ variables $x_1, x_2, \ldots, x_{n-1}$. The distinction is sharp. If there are large numbers of breaks possible, the distinction becomes very important as the two "machines" will usually be profoundly different in properties).

There is therefore complete correspondence between the properties of breaks and those of step-functions, and the final definition of a break is as follows: If, in a dynamic organisation (as defined above), one of the variables is a step-function of the time, then at the moment when it changes value we may, if we like, say that the machine composed of the other variables "broke" at that moment and formed a new machine.

We may now examine in more detail the conditions under which the break will occur. If v is a continuous function of the x's, the surface

$$v(x_1, \ldots, x_n) = 0$$

will divide up the x-space into regions so that on one side of the surface the step-function has one value and on the other side of the surface the other value. Now examine v in the $(n - 1)$-dimensional space of $x_1, x_2, \ldots, x_{n-1}$, *i.e.*, the space of the machine which breaks. There will be two surfaces possible:

$$v(x_1, \ldots, x_{n-1}, x_n^0) = 0$$

and

$$v(x_1, \ldots, x_{n-1}, x_n^1) = 0$$

only one of which can exist at a time. Such a surface is called a "break-surface".

The importance of a break-surface is that it specifies the conditions under which x_n will break, *i.e.*, change value. Thus, suppose the machine starts with x_n at x_n^0, then as long as the representative point does not cross that surface, so long will x_n remain at x_n^0, *i.e.*, so long will the machine remain unbroken. Should the point cross the surface, then x_n will change to x_n^1 and the machine will break. (What happens after the break depends on the position of the other break-surface. If, as often happens, it is entirely at infinity, then the break is irreversible).

§ 5. *Equilibrium.*

The usual elementary definitions of equilibrium (*e.g.*, " that the vector sum of the forces is zero ") are of no use here for we are considering more general systems, and such a definition could not be applied even to a thermostat, for instance, though the latter exhibits obvious equilibrium. (The concepts of " neutral " and " unstable " equilibrium are of little interest here and will not be considered). More general definitions seem to be lacking, though the essential idea is clearly stated by Lorentz (1927) : " By a state of equilibrium of a system we mean a state in which it can persist permanently ".

Ordinary equilibrium is an example of the physicist's concept of a "steady state ", of which the essential property is that, from some configuration onwards, the variables concerned are always bounded. But this general definition makes possible all sorts of curious special cases, physically rare but mathematically possible. In practice, " equilibrium " usually refers to a sub-case, defined here as occurring when a part of the field in the x-space is filled with paths all of which converge to and terminate at one point. It may be shown that, under the conditions discussed later in this paper, it is more probable than other steady states.

Equilibrium has some special properties which we must notice. Firstly, since the paths lead inward, the system tends to the configuration represented by the central point ; so if it is disturbed slightly from this it will automatically develop internal actions or tendencies bringing it back to that state. In other words, it appears to oppose any disturbance from that state. Further, if we disturb it in different ways (*i.e.*, displace the representative point in different directions) it will develop different tendencies with different disturbances, the tendencies being always adjusted to the disturbance so as to oppose it. Clearly this is characteristic of any system in equilibrium whether living or dead.

§ 6. *Machines in Time.*

We have now completed the necessary framework and can handle with quantitative accuracy questions relating to machines, equilibria, and breaks. We proceed to develop a fundamental principle by asking the simple question : " What happens to dynamic organisations in time ? "

The usual answer is that the system moves for ever according to the equations governing it. But this answer is no longer satisfactory when we use the concept of a " break ". The idea of variables increasing indefinitely far is a mathematician's extrapolation, and it does not correspond with what happens in real dynamic systems ; not, at least, in the type of system we are considering here. Thus, quicker movements in a machine lead, if fast enough, to mechanical breaks ; increasing electric currents or potentials lead to the fusing of wires or the breakdown of insulation ; increasing pressures lead to bursts ; increasing temperatures lead to the apparatus itself melting ; even in chemical dynamics, increasing concentrations lead to saturation complications or changes of phase (a break as defined above). It is therefore a common observation that machines break if their variables go far enough.

Under these conditions every machine must end at some equilibrium. Thus, suppose we start with a great number of haphazardly assembled machines which are given random configurations and then started. Those which are tending towards equilibria will arrive at them and will then *stop there.* But what of the others, some of whose variables are increasing indefinitely ? In practice the result is invariable—something breaks. After a break the organisation is changed, and therefore so are the equilibria. This gives the machine fresh chances of moving to the new equilibrium or, if not, of breaking again. It is as if a gambling game were being played with the curious rule of

Heads—I win ; Tails—we toss again !

Clearly there is only one practical ending. This may be stated in the approximate but arresting form : dynamic systems stop breaking when, and only when, they reach a state of equilibrium. And since a break is a change of organisation the principle may be restated in the equivalent form : if we allow breaks to occur, then all dynamic systems change their organisations until they arrive at a state of equilibrium.

It is important to note that up to this point we have made no special hypothesis at all. The principles described are common and necessary to all machines whatever.

We now examine the behaviour of a machine with a large number of breaks available, the conditions of break, *i.e.*, the break-surfaces, being all approximately the same. (This will tend to occur if the machine is built up of great numbers of small parts which are all approximately similar to one another). Under these conditions, the machine is bound to end at an equilibrium whose paths avoid the break-surfaces : the reason being that if the point follows a path meeting the surfaces, a break occurs, and the old field is destroyed. Only a path avoiding the break-surfaces can survive. In this way *a layer of break-surfaces acts as a barrier to the representative point.*

Finally, suppose the break-surfaces surround a given region of the x-space completely. Start with the representative point within the region. We then follow it as before : If the point reaches an equilibrium within the given region, it stops there. If not, it will cause breaks until eventually a field arrives with an equilibrium within the region. Only when this arrives can the system stop breaking. It is clear, therefore. that a layer of break-surfaces round a given region will automatically alter the field until there is an equilibrium within the given region. Again we may re-state this in terms of organisation : *A layer of break-surfaces round a given region will automatically ensure the establishment of an organisation having an equilibrium within the given region.*

This is the point of the whole paper.

§ 7. *Application to Living Organisms.*

It has been shown in the previous section that machines with large numbers of breaks available have, in consequence, certain highly characteristic properties—properties not hitherto studied. To what extent may these properties be regarded as solving the problem we started with ? As stated in § 2 it was : " How does the nervous system develop such an organisation internally that, as a machine it shall be in equilibrium with its environment, the equilibrium keeping all important variables within certain (physiological) limits ? "

My answer is simple : let it, as a machine, break every time the variables go outside these limits. Then by the proofs of § 6 the nervous system is bound to develop the features required. But this needs amplification.

(*a*) Firstly, is the animal a "machine" in our sense ? The animal by itself is incomplete, the environment being an essential part of the whole system. Without an environment, behaviour on the part of the animal would be both causeless and effectless. But when we have both animal and environment included, then the system is complete and the two form a machine in our sense. (It should be noted that we now make no essential distinction between the animal and its environment : both contribute to the organisation of the whole, both act dynamically on themselves and on the other, any equilibrium must stabilise both, and as physical systems the above principles must govern both).

In the nervous system the "variables" are mostly impulse-frequencies at various points in the nerve-network. And as the impulses at one point affect in various ways the impulse-frequencies at other points, the nervous system is a dynamic system par excellence.

(*b*) The next question is to ask what "breaks" there are available in the nervous system. A first reply is that there must be breaks present, since it may be proved that there is no other way in which an isolated machine can change its organisation.

And we must not overlook the fact that the precise physiological nature of the breaks is, for our purpose, of no importance. The properties we have proved are true for all breaks whatever, *i.e.*, for all physical variables which behave as step-functions.

But it does not seem improbable to suppose that neurons have breaks available. The delicacy of the finer dendrons and of the "pieds terminaux", the richness of the cells in protein-lipoid membranes, some of which may be mono-molecular in thickness, and the presence of fibrils are all suggestive. More definitely, Speidel's (1942) observation that nerve endings can be amoeboid, confirming *in vivo* what was observed in tissue culture, provides for my theory an almost ideal mechanism to embody the principles.

(*c*) The necessity in the theory that the breaks should be consistent is satisfied with reasonable probability since the cells of the nervous system are not likely to be all entirely different from one another in regard to their basic physiological properties.

(*d*) The large number of breaks required by theory may be supplied by each neuron, but a feature contributing to the same end is that, as a high intensity of excitation in one cell is likely to be followed by a high excitation in other cells to which it is joined, high excitations in one cell may tend to cause breaks in other cells, thus having the effect, relatively, of increasing the number of breaks available. Another fact having the same effect is that comparatively few breaks will supply a great number of organisations.

(*e*) The "region" of § 6 is around that configuration in which all neurons are stimulated at an intensity below that at which breaks start to occur. This means that, according to theory, the nervous system must always keep changing its organisation until it reaches an equilibrium with all neurons (and particularly receptors) stimulated to less than some particular degree. What this degree is must be laid down by heredity: it will depend on the primary physiological necessities of the animal. But it may usually be assumed that any activity which prevents the receptors from being excessively stimulated will protect the animal from immediate physical danger. (Though tasteless poisons soon demonstrate that the protection is not absolute).

(*f*) We may summarise this section by pointing out that each requirement of theory has been shown, in (*a*) to (*e*), to be parallelled by a known property of the nervous system.

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Finally, the author is well aware that this theory needs considerable elaboration and development in order to make it fit better the actual properties of living things. The theory is markedly lacking in some directions, some of which are in process of being corrected. But the theory seems to be complete, as far as it goes, in the elementary cases and this, though simple, provides at least a solid foundation for the future.

Summary.

An outstanding property of the higher nervous system is that, in contact with a new and previously unexperienced environment, it develops and produces behaviour which is adapted to that environment. It is usually assumed that the behaviour depends on the development of an inner, neuronic organisation. But considering that the neurons might as easily develop one of the almost infinite wrong organisations, the fact that the right one is developed calls for explanation. Why should a network of neurons produce adaptive instead of chaotic behaviour ? Psychology cannot rest content until it has found a *physical* answer to this problem.

The author has approached this problem from the point of view that the brain is a physical machine, and that " adaptive " behaviour is that which maintains it in physical equilibrium with its environment. This basic theme has been studied with all possible generality and precision. This has necessitated the construction of a special mathematical technique, and this has led to a number of new theorems on equilibrium and organisation in generalised dynamic systems.

The problem of a self-equilibrating physical system can now be attacked with both rigor and generality. The paper then shows how these new methods provide an essentially simple and clear-cut solution to the problem.

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