V Computing Machines and the Nervous System

Computing machines are essentially machines for recording numbers, operating with numbers, and giving the result in numerical form. A very considerable part of their cost, both in money and in the effort of construction, goes to the simple problem of recording numbers clearly and accurately. The simplest mode of doing this seems to be on a uniform scale, with a pointer of some sort moving over this. If we wish to record a number with an accuracy of one part in n, we have to assure that in each region of the scale the pointer assumes the desired position within this accuracy. That is, for an amount of information $\log_2 n$, we must finish each part of the movement of the pointer with this degree of accuracy, and the cost will be of the form An, where A is not too far from a constant. More precisely, since if $n - 1$ regions are accurately established, the remaining region will also be determined accurately, the cost of recording an amount of information I will be about

$$\left(2^I - 1\right) A \tag{5.01}$$

Now let us divide this information over two scales, each marked less accurately. The cost of recording this information will be about

$$2\left(2^{I/2}-1\right)A \tag{5.02}$$

If the information be divided among N scales, the approximate cost will be

$$N\left(2^{I/N}-1\right)A \tag{5.03}$$

This will be a minimum when

$$2^{I/N}-1=\frac{I}{N}2^{I/N}\log 2 \tag{5.04}$$

or if we put

$$\frac{I}{N}\log 2 = x \tag{5.05}$$

when

$$x=\frac{e^{x}-1}{e^{x}}=1-e^{-x} \tag{5.06}$$

This will occur when and only when $x = 0$, or $N = \infty$. That is, N should be as large as possible to give the lowest cost for the storage of information. Let us remember that $2^{I/N}$ must be an integer, and that 1 is not a significant value, as we then have an infinite number of scales each containing no information. The best significant value for $2^{I/N}$ is 2, in which case we record our number on a number of independent scales, each divided into two equal parts. In other words, we represent our numbers in the binary system on a number of scales in which all that we know is that a certain quantity lies in one or the other of two equal portions of the scale, and in which the probability of an imperfect knowledge as to which half of the scale contains the observation is made vanishingly small. In other words, we represent a number v in the form

$$v = v_0 + \frac{1}{2} v_1 + \frac{1}{2^2} v_2 + \cdots + \frac{1}{2_n} v_n + \cdots \tag{5.07}$$

where every v_n is either 1 or 0.

There exist at present two great types of computing machines: those like the Bush differential analyzer,[1] which are known as *analogy machines*, where the data are represented by measurements on some continuous scale, so that the accuracy of the machine is determined by the accuracy of construction of the scale; and those, like the ordinary desk adding and multiplying machine, which we call *numerical machines*, where the data are represented by a set of choices among a number of contingencies, and the accuracy is determined by the sharpness with which the contingencies are distinguished, the number of alternative contingencies presented at every choice, and the number of choices given. We see that for highly accurate work, at any rate, the numerical machines are preferable, and above all, those numerical machines constructed on the binary scale, in which the number of alternatives presented at each choice is two. Our use of machines on the decimal scale is conditioned merely by the historical accident that the scale of ten, based on our fingers and thumbs, was already in use when the Hindus made the great discovery of the importance of the zero and the advantage of a positional system of notation. It is worth retaining when a large part of the work done with the aid of the machine consists in transcribing onto the machine numbers in the conventional decimal form, and in taking off the machine numbers which must be written in the same conventional form.

This is, in fact, the use of the ordinary desk computing machine, as employed in banks, in business offices, and in many statistical laboratories. It is not the way that the larger and more automatic machines are best to be employed; in general, any computing machine is used because machine methods are faster than hand methods. In any combined use of means of computation, as in any combination of chemical reactions, it is the slowest which gives the order of magnitude of the time constants of the entire system. It is thus advantageous, as far as possible, to remove the human element from any elaborate chain of computation and to introduce it only where it is absolutely unavoidable, at the very beginning and the very end. Under these conditions, it pays to have an instrument for the change of the scale of notation, to be used initially and finally in the chain of computations, and to perform all intermediate processes on the binary scale.

The ideal computing machine must then have all its data inserted at the beginning, and must be as free as possible from human interference to the very end. This means that not only must the numerical data be inserted at the beginning, but also all the rules for combining them, in the form of instructions covering every situation which may arise in the course of the computation. Thus the computing machine must be a logical machine as well as an arithmetic machine and must combine contingencies in accordance with a systematic algorithm. While there are many algorithms which *might* be used for combining contingencies, the simplest of these is known as the algebra of logic *par excellence*, or the Boolean algebra. This algorithm, like the binary arithmetic, is based on the dichotomy, the choice between *yes* and *no*, the choice between being in a class and outside. The reasons for its superiority to other systems are of the same nature as the reasons for the superiority of the binary arithmetic over other arithmetics.

Thus all the data, numerical or logical, put into the machine are in the form of a set of choices between two alternatives, and all the operations on the data take the form of making a set of new choices depend on a set of old choices. When I add two one-digit numbers, A and B, I obtain a two-digit number commencing with 1, if A and B are both 1, and otherwise with 0. The second digit is 1 if $A \neq B$, and is otherwise 0. The addition of numbers of more than one digit follows similar but more complicated rules. Multiplication in the binary system, as in the decimal, may be reduced to the multiplication table and the addition of numbers, and the rules for multiplication for binary numbers take on the peculiarly simple form given by the table

×	0	1
0	0	0
1	0	1

(5.08)

Thus multiplication is simply a method to determine a set of new digits when old digits are given.

On the logical side, if O is a negative and I a positive decision, every operator can be derived from three: *negation*, which transforms I into O and O into I; *logical addition*, with the table

$\oplus$	O	I
O	O	I
I	I	I

(5.09)

and *logical multiplication*, with the same table as the numerical multiplication of the (1, 0) system, namely,

$\odot$	O	I
O	O	O
I	O	I

(5.10)

That is, every contingency which may arise in the operation of the machine simply demands a new set of choices of contingencies *I* and *O*, depending according to a fixed set of rules on the decisions already made. In other words, the structure of the machine is that of a bank of relays, capable each of two conditions, say "on" and "off"; while at each stage the relays assume each a position dictated by the positions of some or all the relays of the bank at a previous stage of operation. These stages of operation may be definitely "clocked" from some central clock or clocks, or the action of each relay may be held up until all the relays which should have acted earlier in the process have gone through all the steps called for.

The relays used in a computing machine may be of very varied character. They may be purely mechanical, or they may be electro-mechanical, as in the case of a solenoidal relay, in which the armature will remain in one of two possible positions of equilibrium until an appropriate impulse pulls it to the other side. They may be purely electrical systems with two alternative positions of equilibrium, either in the form of gas-filled tubes, or, what is much more rapid, in the form of high-vacuum tubes. The two possible states of a relay system may both be stable in the absence of outside interference, or only one may be stable, while the other is transitory. Always in the second case and generally in the first case, it will be desirable to have special apparatus to retain an impulse which is to act at some future time, and to avoid the clogging up of the system which will ensue if one of the relays does nothing but repeat itself indefinitely. However, we shall have more to say concerning this question of memory later.

It is a noteworthy fact that the human and animal nervous systems, which are known to be capable of the work of a computation system, contain elements which are ideally suited to act as relays. These elements are the so-called *neurons* or nerve cells. While they show rather complicated properties under the influence of electrical currents, in their ordinary physiological action they conform very nearly to the "all-or-none" principle; that is, they are either at rest, or when they "fire" they go through a series of changes almost independent of the nature and intensity of the stimulus. There is first an active phase, transmitted from one end to the other of the neuron with a definite velocity, to which there succeeds a refractory period during which the neuron is either incapable of being stimulated, or at any rate is not capable of being stimulated by any normal, physiological process. At the end of this effective refractory period, the nerve remains inactive, but may be stimulated again into activity.

Thus the nerve may be taken to be a relay with essentially two states of activity: firing and repose. Leaving aside those neurons which accept their messages from free endings or sensory end organs, each neuron has its message fed into it by other neurons at points of contact known as *synapses*. For a given outgoing neuron, these vary in number from a very few to many hundred. It is the state of the incoming impulses at the various synapses, combined with the antecedent state of the outgoing neuron itself, which determines whether it will fire or not. If it is neither firing nor refractory, and the number of incoming synapses which "fire" within a certain very short fusion interval of time exceeds a certain threshold, then the neuron will fire after a known, fairly constant synaptic delay.

This is perhaps an oversimplification of the picture: the "threshold" may not depend simply on the number of synapses but on their "weight" and their geometrical relations to one another with respect to the neuron into which they feed; and there is very convincing evidence that there exist synapses of a different nature, the so-called "inhibitory synapses," which either completely prevent the firing of the outgoing neuron or at any rate raise its threshold with respect to stimulation at the ordinary synapses. What is pretty clear, however, is that some definite combinations of impulses on the incoming neurons having synaptic connections with a given neuron will cause it to fire, while others will not cause it to fire. This is not to say that there may not be other, non-neuronic influences, perhaps of a humoral nature, which produce slow, secular changes tending to vary that pattern of incoming impulses which is adequate for firing.

A very important function of the nervous system, and, as we have said, a function equally in demand for computing machines, is that of *memory*, the ability to preserve the results of past operations for use in the future. It will be seen that the uses of the memory are highly various, and it is improbable that any single mechanism can satisfy the demands of all of them. There is first the memory which is necessary for the carrying out of a current process, such as a multiplication, in which the intermediate results are of no value once the process is completed, and in which the operating apparatus should then be released for further use. Such a memory should record quickly, be read quickly, and be erased quickly. On the other hand, there is the memory which is intended to be part of the files, the permanent record, of the machine or the brain, and to contribute to the basis of all its future behavior, at least during a single run of the machine. Let it be remarked parenthetically that an important difference between the way in which we use the brain and the machine is that the machine is intended for many successive runs, either with no reference to each other, or with a minimal, limited reference, and that it can be cleared between such runs; while the brain, in the course of nature, never even approximately clears out its past records. Thus the brain, under normal circumstances, is not the complete analogue of the computing machine but rather the analogue of a single run on such a machine. We shall see later that this remark has a deep significance in psychopathology and in psychiatry.

To return to the problem of memory, a very satisfactory method for constructing a short-time memory is to keep a sequence of impulses traveling around a closed circuit until this circuit is cleared by intervention from outside. There is much reason to believe that this happens in our brains during the retention of impulses, which occurs over what is known as the specious present. This method has been imitated in several devices which have been used in computing machines, or at least suggested for such a use. There are two conditions which are desirable in such a retentive apparatus: the impulse should be transmitted in a medium in which it is not too difficult to achieve a considerable time lag; and before the errors inherent in the instrument have blurred it too much, the impulse should be reconstructed in a form as sharp as possible. The first condition tends to rule out delays produced by the transmission of light, or even, in many cases, by electric circuits, while it favors the use of one form or another of elastic vibrations; and such vibrations have actually been employed for this purpose in computing machines. If electric circuits are used for delay purposes, the delay produced at every stage is relatively short; or, as in all pieces of linear apparatus, the deformation of the message is cumulative and very soon becomes intolerable. To avoid this, a second consideration comes into play; we must insert somewhere in the cycle a relay which does not serve to repeat the form of the incoming message but rather to trigger off a new message of prescribed form. This is done very easily in the nervous system, where indeed all transmission is more or less of a trigger phenomenon. In the electrical industry, pieces of apparatus for this purpose have long been known and have been used in connection with telegraph circuits. They are known as *telegraph-type repeaters*. The great difficulty of using them for memories of long duration is that they have to function without a flaw over an enormous number of consecutive cycles of operation. Their success is all the more remarkable: in a piece of apparatus designed by Mr. Williams of the University of Manchester, a device of this sort with a unit delay of the order of a hundredth of a second has continued in successful operation for several hours. What makes this more remarkable is that this apparatus was not used merely to preserve a single decision, a single "yes" or "no," but a matter of thousands of decisions.

Like other forms of apparatus intended to retain a large number of decisions, this works on the scanning principle. One of the simplest modes of storing information for a relatively short time is as the charge on a condenser; and when this is supplemented by a telegraph-type repeater, it becomes an adequate method of storage. To use to the best advantage the circuit facilities attached to such a storage system, it is desirable to be able to switch successively and very rapidly from one condenser to another. The ordinary means of doing this involve mechanical inertia, and this is never consistent with very high speeds. A much better way is the use of a large number of condensers, in which one plate is either a small piece of metal sputtered into a dielectric, or the imperfectly insulating surface of the dielectric itself, while one of the connectors to these condensers is a pencil of cathode rays moved by the condensers and magnets of a sweep circuit over a course like that of a plough in a ploughed field. There are various elaborations of this method, which indeed was employed in a somewhat different way by the Radio Corporation of America before it was used by Mr. Williams.

These last-named methods for storing information can hold a message for quite an appreciable time, if not for a period comparable with a human lifetime. For more permanent records, there is a wide variety of alternatives among which we can choose. Leaving out such bulky, slow, and unerasable methods as the use of punched cards and punched tape, we have magnetic tape, together with its modern refinements, which have largely eliminated the tendency of messages on this material to spread; phosphorescent substances; and above all, photography. Photography is indeed ideal for the permanence and detail of its records, ideal again from the point of view of the shortness of exposure needed to record an observation. It suffers from two grave disadvantages: the time needed for development, which has been reduced to a few seconds, but is still not small enough to make photography available for a short-time memory; and (at present [1947]) the fact that a photographic record is not subject to rapid erasure and the rapid implanting of a new record. The Eastman people have been working on just these problems, which do not seem to be necessarily insoluble, and it is possible that by this time they have found the answer.

Very many of the methods of storage of information already considered have an important physical element in common. They seem to depend on systems with a high degree of quantum degeneracy, or, in other words, with a large number of modes of vibration of the same frequency. This is certainly true in the case of ferromagnetism, and is also true in the case of materials with an exceptionally high dielectric constant, which are thus especially valuable for use in condensers for the storage of information. Phosphorescence as well is a phenomenon associated with a high quantum degeneracy, and the same sort of effect makes its appearance in the photographic process, where many of the substances which act as developers seem to have a great deal of internal resonance. Quantum degeneracy appears to be associated with the ability to make small causes produce appreciable and stable effects. We have already seen in Chapter II that substances with high quantum degeneracy appear to be associated with many of the problems of metabolism and reproduction. It is probably not an accident that here, in a non-living environment, we find them associated with a third fundamental property of living matter: the ability to receive and organize impulses and to make them effective in the outer world.

We have seen in the case of photography and similar processes that it is possible to store a message in the form of a permanent alteration of certain storage elements. In reinserting this information into the system, it is necessary to cause these changes to affect the messages going through the system. One of the simplest ways to do this is to have, as the storage elements which are changed, parts which normally assist in the transmission of messages, and of such a nature that the change in their character due to storage affects the manner in which they will transport messages for the entire future. In the nervous system, the neurons and the synapses are elements of this sort, and it is quite plausible that information is stored over long periods by changes in the thresholds of neurons, or, what may be regarded as another way of saying the same thing, by changes in the permeability of each synapse to messages. Many of us think, in the absence of a better explanation of the phenomenon, that the storage of information in the brain can actually occur in this way. It is conceivable for such a storage to take place either by the opening of new paths or by the closure of old ones. Apparently it is adequately established that no neurons are formed in the brain after birth. It is possible, though not certain, that no new synapses are formed, and it is a plausible conjecture that the chief changes of thresholds in the memory process are increased. If this is the case, our whole life is on the pattern of Balzac's *Peau de Chagrin*, and the very process of learning and remembering exhausts our powers of learning and remembering until life itself squanders our capital stock of power to live. It may well be that this phenomenon does occur. This is a possible explanation for a sort of senescence. The real phenomenon of senescence, however, is much too complicated to be explained in this way alone.

We have already spoken of the computing machine, and consequently the brain, as a logical machine. It is by no means trivial to consider the light cast on logic by such machines, both natural and artificial. Here the chief work is that of Turing.[2] We have said before that the *machina ratiocinatrix* is nothing but the *calculus ratiocinator* of Leibniz with an engine in it; and just as modern mathematical logic begins with this calculus, so it is inevitable that its present engineering development should cast a new light on logic. The science of today is operational; that is, it considers every statement as essentially concerned with possible experiments or observable processes. According to this, the study of logic must reduce to the study of the logical machine, whether nervous or mechanical, with all its non-removable limitations and imperfections.

It may be said by some readers that this reduces logic to psychology, and that the two sciences are observably and demonstrably different. This is true in the sense that many psychological states and sequences of thought do not conform to the canons of logic. Psychology contains much that is foreign to logic, but—and this is the important fact—any logic which means anything to us can contain nothing which the human mind—and hence the human nervous system—is unable to encompass. *All logic is limited by the limitations of the human mind when it is engaged in that activity known as logical thinking.*

For example, we devote much of mathematics to discussions involving the infinite, but these discussions and their accompanying proofs are not infinite in fact. No admissible proof involves more than a finite number of stages. It is true, a proof by mathematical induction *seems* to involve an infinity of stages, but this is only apparent. In fact, it involves just the following stages:

1. P_n is a proposition involving the number n.
2. P_n has been proved for $n = 1$.
3. If P_n is true, P_{n+1} is true.
4. Therefore, P_n is true for every positive integer n.

It is true that somewhere in our logical assumptions there must be one which validates this argument. However, this mathematical induction is a far different thing from complete induction over an infinite set. The same thing is true of the more refined forms of mathematical induction, such as transfinite induction, which occur in certain mathematical disciplines.

Thus some very interesting situations arise, in which we may be able—with enough time and enough computational aids—to prove every single case of a theorem P_n; but if there is no systematic way of subsuming these proofs under a single argument independent of n, such as we find in mathematical induction, it may be impossible to prove P_n *for all* n. This contingency is recognized in what is known as metamathematics, the discipline so brilliantly developed by Gödel and his school.

A proof represents a logical process which has come to a definitive conclusion in a finite number of stages. However, a logical machine following definite rules need never come to a conclusion. It may go on grinding through different stages without ever coming to a stop, either by describing a pattern of activity of continually increasing complexity, or by going into a repetitive process like the end of a chess game in which there is a continuing cycle of perpetual check. This occurs in the case of some of the paradoxes of Cantor and Russell. Let us consider the class of all classes which are not members of themselves. Is this class a member of itself? If it is, it is certainly not a member of itself; and if it is not, it is equally certainly a member of itself. A machine to answer this question would give the successive temporary answers: “yes,” “no,” “yes,” “no,” and so on, and would never come to equilibrium.

Bertrand Russell’s solution of his own paradoxes was to affix to every statement a quantity, the so-called type, which serves to distinguish between what seems to be formally the same statement, according to the character of the objects with which it concerns itself—whether these are “things,” in the simplest sense, classes of “things,” classes of classes of “things,” etc. The method by which we resolve the paradoxes is also to attach a parameter to each statement, this parameter being the time at which it is asserted. In both cases, we introduce what we may call a parameter of uniformization, to resolve an ambiguity which is simply due to its neglect.

We thus see that the logic of the machine resembles human logic, and, following Turing, we may employ it to throw light on human logic. Has the machine a more eminently human characteristic as well—the ability to learn? To see that it may well have even this property, let us consider two closely related notions: that of the association of ideas and that of the conditioned reflex.

In the British empirical school of philosophy, from Locke to Hume, the content of the mind was considered to be made up of certain entities known to Locke as ideas, and to the later authors as ideas and impressions. The simple ideas or impressions were supposed to exist in a purely passive mind, as free from influence on the ideas it contained as a clean blackboard is on the symbols which may be written on it. By some sort of inner activity, hardly worthy to be called a force, these ideas were supposed to unite themselves into bundles, according to the principles of similarity, contiguity, and cause and effect. Of these principles, perhaps the most significant was contiguity: ideas or impressions which had often occurred together in time or in space were supposed to have acquired the ability of evoking one another, so that the presence of any one of them would produce the entire bundle.

In all this there is a dynamics implied, but the idea of a dynamics had not yet filtered through from physics to the biological and psychological sciences. The typical biologist of the eighteenth century was Linnaeus, the collector and classifier, with a point of view quite opposed to that of the evolutionists, the physiologists, the geneticists, the experimental embryologists of the present day. Indeed, with so much of the world to explore, the state of mind of the biologists could hardly have been different. Similarly, in psychology, the notion of mental content dominated that of mental process. This may well have been a survival of the scholastic emphasis on substances, in a world in which the noun was hypostasized and the verb carried little or no weight. Nevertheless, the step from these static ideas to the more dynamic point of view of the present day, as exemplified in the work of Pavlov, is perfectly clear.

Pavlov worked much more with animals than with men, and he reported visible actions rather than introspective states of mind. He found in dogs that the presence of food causes the increased secretion of saliva and of gastric juice. If then a certain visual object is shown to dogs in the presence of food and only in the presence of food, the sight of this object in the absence of food will acquire the property of being by itself able to stimulate the flow of saliva or of gastric juice. The union by continguity which Locke had observed introspectively in the case of ideas now becomes a similar union of patterns of behavior.

There is one important difference, however, between the point of view of Pavlov and that of Locke, and it is precisely due to this fact that Locke considers ideas and Pavlov patterns of action. The responses observed by Pavlov tend to carry a process to a successful conclusion or to avoid a catastrophe. Salivation is important for deglutition and for digestion, while the avoidance of what we should consider a painful stimulus tends to protect the animal from bodily injury. Thus there enters into the conditioned reflex something that we may call *affective tone*. We need not associate this with our own sensations of pleasure and pain, nor need we in the abstract associate it with the advantage of the animal. The essential thing is this: that affective tone is arranged on some sort of scale from negative "pain" to positive "pleasure"; that for a considerable time, or permanently, an increase in affective tone favors all processes in the nervous system that are under way at the time and gives them a secondary power to increase affective tone; and that a decrease in affective tone tends to inhibit all processes under way at the time and gives them a secondary ability to decrease affective tone.

Biologically speaking, of course, a greater affective tone must occur predominantly in situations favorable for the perpetuation of the race, if not the individual, and a smaller affective tone in situations which are unfavorable for this perpetuation, if not disastrous. Any race not conforming to this requirement will go the way of Lewis Carroll's Bread-and-Butter Fly, and always die. Nevertheless, even a doomed race may show a mechanism valid so long as the race lasts. In other words, even the most suicidal apportioning of affective tone will produce a definite pattern of conduct.

Note that the mechanism of affective tone is itself a feedback mechanism. It may even be given a diagram such as shown in Fig. 7.

Here the totalizer for affective tone combines the affective tones given by the separate affective-tone mechanisms over a short interval in the past, according to some rule which we need not specify now. The leads back to the individual affective-tone

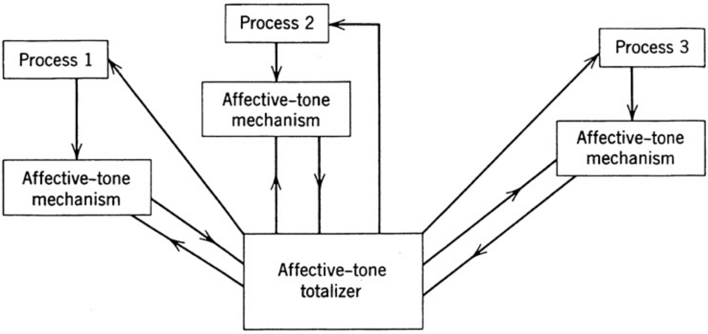

Fig. 7

mechanisms serve to modify the intrinsic affective tone of each process in the direction of the output of the totalizer, and this modification stands until it is modified by later messages from the totalizer. The leads back from the totalizer to the process mechanisms serve to lower thresholds if the total affective tone is increasing, and to raise them if the total affective tone is decreasing. They likewise have a longtime effect, which endures until it is modified by another impulse from the totalizer. This lasting effect, however, is confined to those processes actually in being at the time the return message arrives, and a similar limitation also applies to the effects on the individual affective-tone mechanisms.

I wish to emphasize that I do not say that the process of the conditioned reflex operates according to the mechanism I have given; I merely say that it *could* so operate. If, however, we assume this or any simular mechanism, there are a good many things we can say concerning it. One is that this mechanism is capable of learning. It has already been recognized that the conditioned reflex is a learning mechanism, and this idea has been used in the behaviorist studies of the learning of rats in a maze. All that is needed is that the inducements or punishments used have, respectively, a positive and a negative affective tone. This is certainly the case, and the experimenter learns the nature of this affective tone by experience, not simply by *a priori* considerations.

Another point of considerable interest is that such a mechanism involves a certain set of messages which go out generally into the nervous system, to all elements which are in a state to receive them. These are the return messages from the affective-tone totalizer, and to a certain extent the messages from the affective-tone mechanisms to the totalizers. Indeed, the totalizer need not be a separate element but may merely represent some natural combinatory effect of messages arriving from the individual affective-tone mechanisms. Now, such messages "to whom it may concern" may well be sent out most efficiently, with a smallest cost in apparatus, by channels other than nervous. In a similar manner, the ordinary communication system of a mine may consist of a telephone central with the attached wiring and pieces of apparatus. When we want to empty a mine in a hurry, we do not trust to this, but break a tube of a mercaptan in the air intake. Chemical messengers like this, or like the hormones, are the simplest and most effective for a message not addressed to a specific recipient. For the moment, let me break into what I know to be pure fancy. The high emotional and consequently affective content of hormonal activity is most suggestive. This does not mean that a purely nervous mechanism is not capable of affective tone and of learning, but it does mean that in the study of this aspect of our mental activity, we cannot afford to be blind to the possibilities of hormonal transmission. It may be excessively fanciful to attach this notion to the fact that in the theories of Freud the memory—the storage function of the nervous system—and the activities of sex are both involved. Sex, on the one hand, and all affective content, on the other, contain a very strong hormonal element. This suggestion of the importance of sex and hormones has been made to me by Dr. J. Lettvin and Mr. Oliver Selfridge, While at present there is no adequate evidence to prove its validity, it is not manifestly absurd in principle.

There is nothing in the nature of the computing machine which forbids it to show conditioned reflexes. Let us remember that a computing machine in action is more than the concatenation of relays and storage mechanisms which the designer has built into it. It also contains the content of its storage mechanisms, and this content is never completely cleared in the course of a single run. We have already seen that it is the run rather than the entire existence of the mechanical structure of the computing machine which corresponds to the life of the individual. We have also seen that in the nervous computing machine it is highly probable that information is stored largely as changes in the permeability of the synapses, and it is perfectly possible to construct artificial machines where information is stored in that way. It is perfectly possible, for example, to cause any message going into storage to change in a permanent or semi-permanent way the grid bias of one or of a number of vacuum tubes, and thus to alter the numerical value of the summation of impulses which will make the tube or tubes fire.

A more detailed account of learning apparatus in computing and control machines, and the uses to which it may be put, may well be left to the engineer rather than to a preliminary book like this one. It is perhaps better to devote the rest of this chapter to the more developed, normal uses of modern computing machines. One of the chief of these is in the solution of partial differential equations. Even linear partial differential equations require the recording of an enormous mass of data to set them up, as the data involve the accurate description of functions of two or more variables. With equations of the hyperbolic type, like the wave equation, the typical problem is that of solving the equation when the initial data are given, and this can be done in a progressive manner from the initial data to the results at any given later time. This is largely true of equations of the parabolic type as well. When it comes to equations of the elliptic type, where the natural data are boundary values rather than initial values, the natural methods of solution involve an iterative process of successive approximation. This process is repeated a very large number of times, so that very fast methods, such as those of the modern computing machine, are almost indispensable.

In non-linear partial differential equations, we miss what we have in the case of the linear equations—a reasonably adequate, purely mathematical theory. Here computational methods are not only important for the handling of particular numerical cases, but, as von Neumann has pointed out, we need them in order to form that acquaintance with a large number of particular cases without which we can scarcely formulate a general theory. To some extent this has been done with the aid of very expensive experimental apparatus, such as wind tunnels. It is in this way that we have become acquainted with the more complicated properties of shock waves, slip surfaces, turbulence, and the like, for which we are scarcely in a position to give an adequate mathematical theory. How many undiscovered phenomena of similar nature there may be, we do not know. The analogue machines are so much less accurate, and in many cases so much slower, than the digital machines that the latter give us much more promise for the future.

It is already becoming clear in the use of these new machines that they demand purely mathematical techniques of their own, quite different from those in use in manual computation or in the use of machines of smaller capacity. For example, even the use of machines for computing determinants of moderately high order or for the simultaneous solution of twenty or thirty simultaneous linear equations shows difficulties which do not arise when we study analogous problems of small order. Unless care is exercised in setting up a problem, these may completely deprive the solution of any significant figures whatever. It is a commonplace to say that fine, effective tools like the ultra-rapid computing machine are out of place in the hands of those not possessing a sufficient degree of technical skill to take full advantage of them. The ultra-rapid computing machine will certainly not decrease the need for mathematicians with a high level of understanding and technical training. In the mechanical or electrical construction of computing machines, there are a few maxims which deserve consideration. One is that mechanisms which are relatively frequently used, such as multiplying or adding mechanisms, should be in the form of relatively standardized assemblages adapted for one particular use and no other, while those of more occasional use should be assembled for the moment of use out of elements also available for other purposes. Closely related to this consideration is the one that in these more general mechanisms the component parts should be available in accordance with their general properties, and should not be allotted permanently to a specific association with other pieces of apparatus. There should be some part of the apparatus, like an automatic telephone-switching exchange, which will search for free components and connectors of the various sorts and allot them as they are needed. This will eliminate much of the very large expense which is due to having a great number of unused elements which cannot be used unless their entire large assembly is used. We shall find this principle is very important when we come to consider traffic problems and overloading in the nervous system.

As a final remark, let me point out that a large computing machine, whether in the form of mechanical or electric apparatus or in the form of the brain itself, uses up a considerable amount of power, all of which is wasted and dissipated in heat. The blood leaving the brain is a fraction of a degree warmer than that entering it. No other computing machine approaches the economy of energy of the brain. In a large apparatus like the Eniac or Edvac, the filaments of the tubes consume a quantity of energy which may well be measured in kilowatts, and unless adequate ventilating and cooling apparatus is provided, the system will suffer from what is the mechanical equivalent of pyrexia, until the constants of the machine are radically changed by the heat, and its performance breaks down. Nevertheless, the energy spent per individual operation is almost vanishingly small, and does not even begin to form an adequate measure of the performance of the apparatus. The mechanical brain does not secrete thought "as the liver does bile," as the earlier materialists claimed, nor does it put it out in the form of energy, as the muscle puts out its activity. Information is information, not matter or energy. No materialism which does not admit this can survive at the present day.

Cybernetics or Control and Communication in the Animal and the Machine

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