The human brain

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Despite the fact that comparisons between the electronic computer and the human brain have become clichés, the constant new advances in computer technology produce new and intriguing analogies. Understanding is far from complete, but more than enough is known to reveal the brain as a device of breathless ingenuity. A device, furthermore, which would appear to be under-utilized by the majority of its should-be proud owners. Understanding is yielding results not only of the behaviour of individuals, but also leading to an understanding of that wholly complementary subject—the behaviour of human groups.

Computer specialists can use familiarity with the technology of their trade as a short-cut to comprehending more about the brain and indeed about group behaviour. This is desirable. A few may remember Kipling's words:

> What should they know of England,
> Who only England know?

and—having read this brief paper—be inspired to study the works of those more qualified than myself.

Let us begin then by regarding the brain as a new product announcement by a computer firm and see where we can get.

We will use the usual headings:

Technology—logic
backwiring
Central processor organization
Input and output equipment
Power supplies
and, most important of all,
Software.

Technology

The elements comprising the system appear to be the nerve cells or *neurons*. These cells have a nucleus, like all living cells, to which is attached on the input side a tree, or bush of relatively short fibres called *dendrites*, while on the output side the cell terminates in what may be a very long fibre—in some cases several feet long. These output tails are called *axons*. Output axons meet the input dendrites of other neurons at points called *synapses*. The synapse is, in effect, a small gap between a swelling at the end of the axon (called a *bouton terminal*) and a foot on the end of a dendrite.

So far this is familiar ground, neuron—package; dendrite—input terminal; axon—output terminal. But there are some surprises in store. A computer package with, say, a dozen inputs would be unusually complex—but in the case of nerve cells there may be anything up to 100,000 synaptic terminals on the dendritic tree of a single neuron. So this is the first shock—the "fan in" of the nerve cell (to use the jargon of computer logic) can be exceedingly large.

Fig. 1 is a picture of some typical neurons taken from J. Z. Young's splendid book *A Model of the Brain* which I thoroughly recommend. There are a great variety of different types of cell—many hundreds or thousands of different types in a brain—whereas computer engineers worry when the variety of packages in a computer exceeds a dozen or so.

In **Fig. 2**, taken from the same book, a synapse is shown in detail. At the top right is the bouton on the end of the axon. And at the bottom left is the dendritic foot. The inset shows the synaptic membrane in greater detail. It is apparent that the wiring junctions are pretty complicated. But are they just junctions?

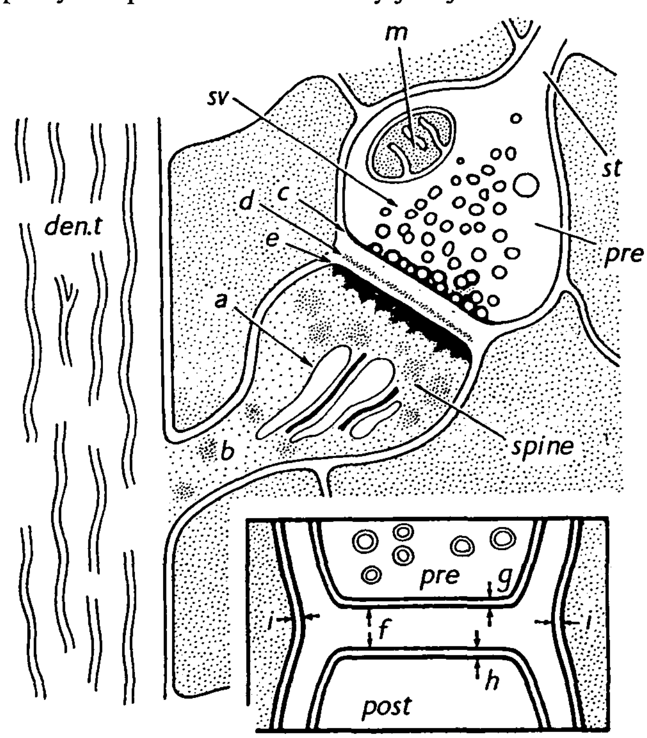

Fig. 2.—Detail of a synapse. Top right is the bouton end of the axon; bottom left is the dendritic foot

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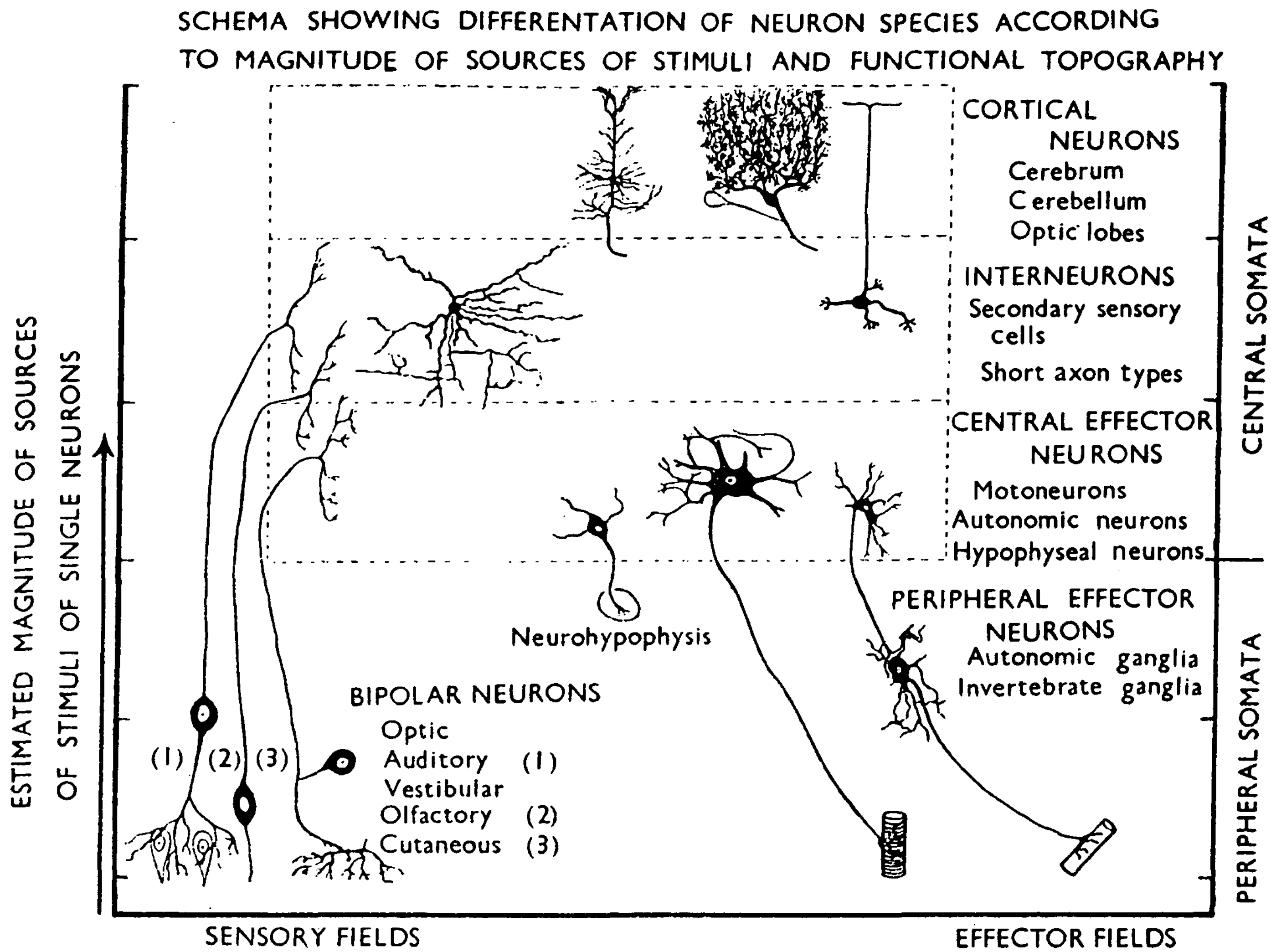

Fig. 1.—Types of neurons occurring in mammals arranged according to function and magnitude of source stimuli

It seems in fact that the synapse is capable of at least some logical operations. A synapse transmits a signal from axon to dendrite depending on the pattern of signals received, both in time and in space. That is to say, a signal or pulse may be transmitted if sufficient signals have been received recently, or if sufficient other signals have occurred at neighbouring synapses on the dendritic tree.

Little is really known about how much of this "summation logic" is associated with the cell as a whole, or with the synapse in particular. Is a neuron then to be regarded as a 1-bit register, or flip-flop, or should a synaptic junction be regarded like this? (There may be 10^5 of them on a neuron.)

Before we settle for either of these simple hypotheses, some of the more fundamental features of the technology should be considered. An obvious difference between computer components and brain cells is the fact that the latter grow and contain their own design data in the RNA molecule. Thus the RNA molecule performs a dual function—genetic and environmental. Not only does it control the initial growth of a cell, it is also utilized for subsequently modifying the "circuits" of the brain and is associated with the learning process.

Each cell, therefore, contains enough information storage capacity to store its own growth program and also, of course, its own fault detection and maintenance programs. The growth program is almost certainly stored as a coded sequence of adenine, thymine, guanine and cystosine groupings along the length of a DNA molecule. Such a molecule may be a thousand times as long as it is wide, and as the scale is in Ångstrom units (ten million to the millimetre) quite a staggering amount of information can be stored in a single molecule.

It seems clear then that the heredity of the cell is associated with information storage at the molecular level. It has also been discovered, however, that the RNA concentration stimulates neuron changes. It is possible therefore that the logical operations taking place at a synapse, or elsewhere in a neuron, may take place through complex chemical reactions involving a considerable number of different nucleic acids, each with a substantial information content. In other words, there is no clear or obvious limit to the logical depth of these natural devices.

Upon examination there appear to be remarkable similarities between the circuit for an electronic gate and the network associated with a neuron, as can be seen in **Fig. 3.** The questions that arise are: Do the inputs from the diodes to the base of a transistor correspond to the inputs from the dendrites to the neuron? Or does the action at the synaptic junction within the bouton terminal correspond more closely to the operation of a transistor gate? Could a synapse, for instance, be considered as a PNP junction with the remarkable property of having an N layer impedance varying with the experience of the cell?

At present it is not known whether the neuron corresponds to a transistor, a package, a shelf of packages, or a whole computer—but it is certainly more than it appears to be at first glance.

So much for the logic. What about the backwiring?

The "wiring" in the brain is accomplished by the axons which provide a mechanism for transmitting a pulse whose physical manifestation is a change in the ionization in the material on either side of the nerve cell wall. The remarkable thing is the manner in which the pulse is constantly regenerated as it passes along the nerve fibre and is not allowed to decay.

However, speed of transmission is quite slow—a foot in three milliseconds compared with one foot per nanosecond (one thousand millionth of a second) in the case of computer information. It is this difference of about three million to one in transmission speed which alone enables computers to compete with brains on equal terms, and only then in a restricted class of suitable problems—typically mathematical problems. In most other cases the brain seems to be able to match the computer by virtue of its capacity to handle many and diverse problems simultaneously, and in its superior capability of retrieving stored information.

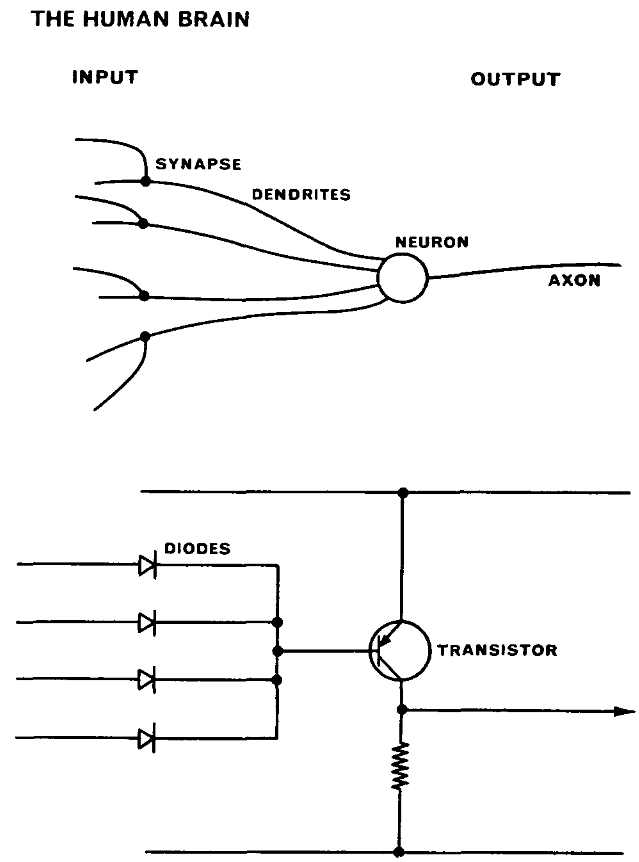

Fig. 3.—Are there similarities between a neuron network and an electronic gate?

Central processor organization

So much for the fine structure of the brain. What about its general organization as a processor? Here again the sheer scale of complexity is somewhat astounding. There are about 10^{10} neurons and probably about 10^{15} synaptic junctions in the human brain. 10^{10}—the number of nerve cells—is about the number of stars in our galaxy. So we have a processor with 10^{10} (or is it 10^{15}?) logical elements, each of unknown logical depth. However, quite early on in the history of modern biology a number of functional areas were identified in the human brain as a result of observations of brain damage and disease. **Fig. 4** is a brain map by Wilder Penfield, the Montreal brain surgeon.

This at once illustrates another major difference between brains and computers. Although the brain certainly contains computing mechanisms of astonishing universality, nevertheless large areas of the brain are functionally specialized.

When children learn to talk it appears to be the case that at least some, and perhaps all, learning involves structural modification of parts of the brain which it may be very difficult to alter later in life. It appears possible, therefore, that the brain evolves its own specialized mechanisms within its life cycle, as well as from generation to generation. Perhaps it should be regarded as a kind of self-wiring computer as well as a collection of interconnected multiprocessing computers.

Nevertheless, the extent of this functional specialization is strangely limited. Thus there is an immense amount of evidence to show that memories and procedures stored in the brain are replicated throughout the whole of a functional area. Limited regions may be essential for the learning or retention of a particular activity, but within such regions the parts appear to be functionally equivalent, so that only substantially total removal of the area destroys the function. In particular, removal of the frontal lobes in man appears to have very much less effect on memory, intelligence and general behaviour than one might expect.

Thus the brain has developed an astonishingly reliable and redundant method of memorizing data, which compares most favourably with the best that engineers are

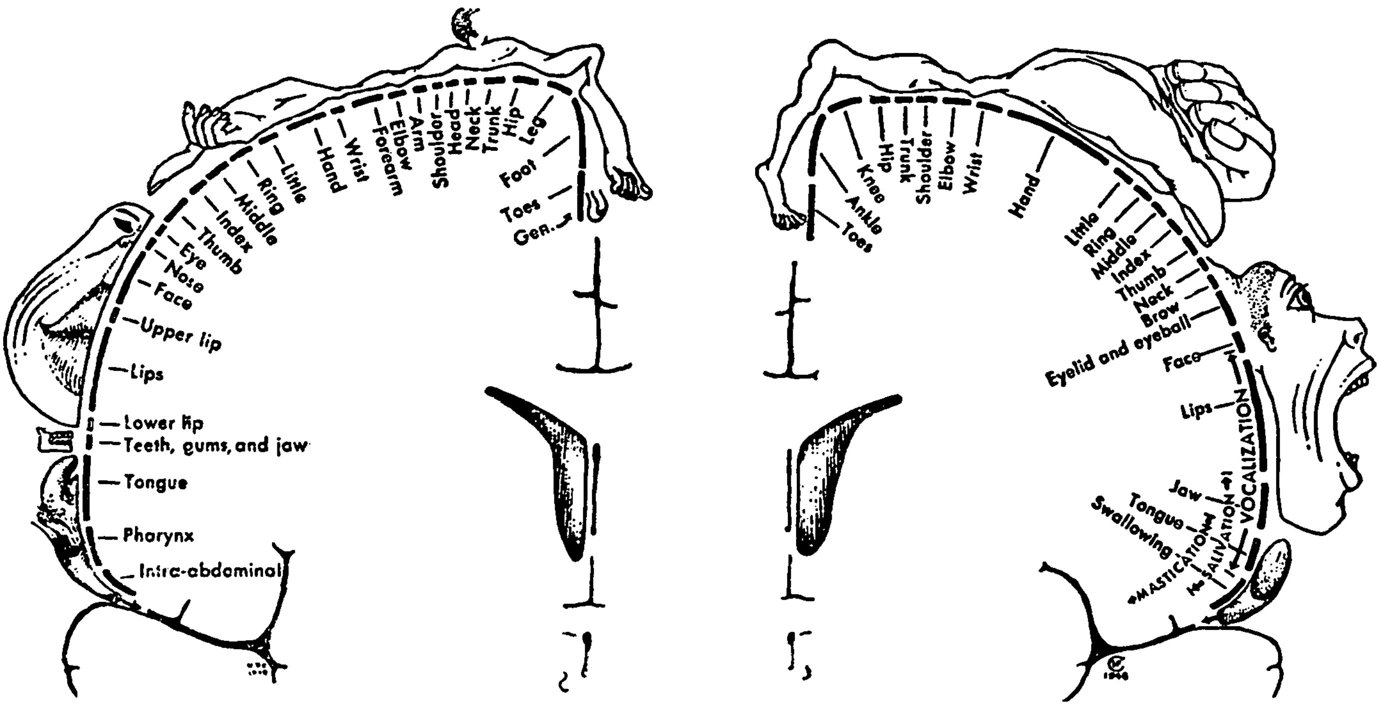

Fig. 4.—Brain map devised by Wilder Penfield, the Montreal brain surgeon

able to achieve with computers. Its general method of functioning is evidently quite different from that with which computer people are technically familiar. Thus we have much to learn from the brain—if only the way in which it really works can be discovered.

Thinking about the functioning of the brain can stimulate ideas. One of the most interesting of these is the concept of a computing network.

Suppose a hexagonal honeycomb net of identical logical elements is constructed. Suppose that each element is in one of a finite number of states at instant t, and that the state of each element at t is some function of the states of this element and the states of its immediate neighbours at a previous instant $t - 1$. Then it can be shown that a suitable function exists which will cause the whole mesh to behave as a digital computer, or indeed any number of computers.

It is assumed that there are certain nodes of the mesh which are conditioned by input signals, and others whose states are outputs. By appropriate conditioning of the input nodes, the network can be set up to represent a computer of entirely arbitrary logical design, or any number of such computers. By suitable reinforcement the existing backwiring can be retained, or by altering the initial activating conditions the backwiring can be changed. This fact is a considerable challenge to the developers of semiconductor technology and may well result in computers which are more like brains—slower perhaps than existing machines but very much more versatile. The number of logical states required at each node is not large—six bits per node provides one of the simpler systems of this type.

Input and output

The output arrangements are fairly straightforward—nerve impulses to operate muscles and so on—though even here there are some unusual methods of output such as causing certain chemical substances to be manufactured in the pituitary and other glands, and injected into the bloodstream as messengers. Some of the effects of emotion are controlled by such means.

An increased heart rate, a rise in blood pressure, dilatation of the pupils of the eyes and flushing of the skin are the signs of the emotion *anger*. Experimental evidence indicates that the physical reactions associated with emotion are activated by nerve cells in a portion of the brain known as the *hypothalamus*. It is the centre from which the body's reaction to emotion is controlled. Past events retained in the memory, current thought processes together with information upon environment received from the body's sense organs, determine the activity of the hypothalamus and hence the emotional response of the body to the situation existing both inside and outside the body. The brain exercises control, and information is effectively conveyed from the brain to the body as nerve impulses and also through adjustments in the chemical activity of the body by the release of substances such as adrenalin and acetylcholine into the blood.

On the input side, the complexity is also enormous. The human eye can resolve about 250,000 distinct points at two intensity levels at a rate of about 18 bits a second per point. This corresponds to sending about five bits a second along each of the million fibres in one optic nerve. Altogether, taking all sensations into account, the brain has to deal with about 10^7 bits a second—equivalent to a data transfer rate associated with ten high-speed magnetic-tape decks operating flat out. This is a very large flow of information, particularly when we remember that, from the work of Dr. Hick, it appears that a human being can only make conscious decisions at a rate of about 5 to 25 very simple decisions a second.

The reason for this great disparity—between the 10^7 bits per second input, and the 25 decisions per second—arises from the fact that

(*a*) not all the input information is relevant,
(*b*) an enormous amount of data reduction is carried out.

In the computer business it is recognized that quite a lot of hardware is associated with peripheral devices—hence the evolution of "standard interfaces" to economize in the design of such hardware. In the brain, however, the hardware (if the term may be used) for peripheral data handling and reduction is continuous with the central processor. Indeed one gets the impression that the central processor has evolved to cope with the peripherals rather than the other way round. In fact there may be a lesson here from which we can benefit.

This peripheral data handling system is located in the visual part of the cerebral cortex—the outer layer, or rind, of the brain. However, the connections to the cortex from the eyes are crossed over, as shown in **Fig. 5.** The illustration depicts Cajal's theory of the origin of this crossing over of both the optic nerves and the motor nerves to the muscles. This enables a panoramic image to be presented to the cortex in a continuous manner as shown, and this emphasizes how the central processor design has been dictated by peripheral considerations.

The visual cortex itself has been the subject of a great deal of research recently and some extremely interesting points have emerged from the work of J. Z. Young on the brain of the octopus, and from Hubel and Wiesel on the brain of the cat. It is quite clear that the cortex must reduce the enormous volume of raw visual data to manageable proportions by a process of encoding. Thus, particular shapes must be recognized and associated with a brief symbol or message describing the essential features of entire shapes. If this is so, then we might expect to find that if an animal looks at a certain type of shape, certain cells are stimulated. This is exactly what Hubel and Wiesel did find in their experiments with micro-electrode responses from particular cells in the visual cortex of the cat. The triangles in the centre of **Fig. 6** show inhibited cells and the crosses excited

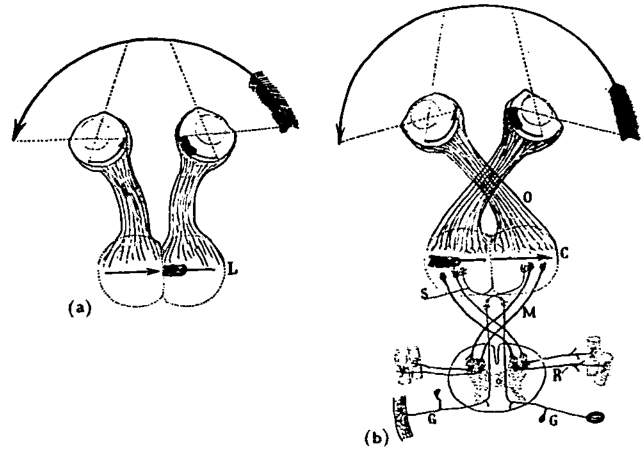

Fig. 5.—Cajal's theory of the crossing of the optic nerves to the brain and the motor nerves from the brain to the muscles. If there were no crossing the panoramic view of the arrow would be split as shown on the left

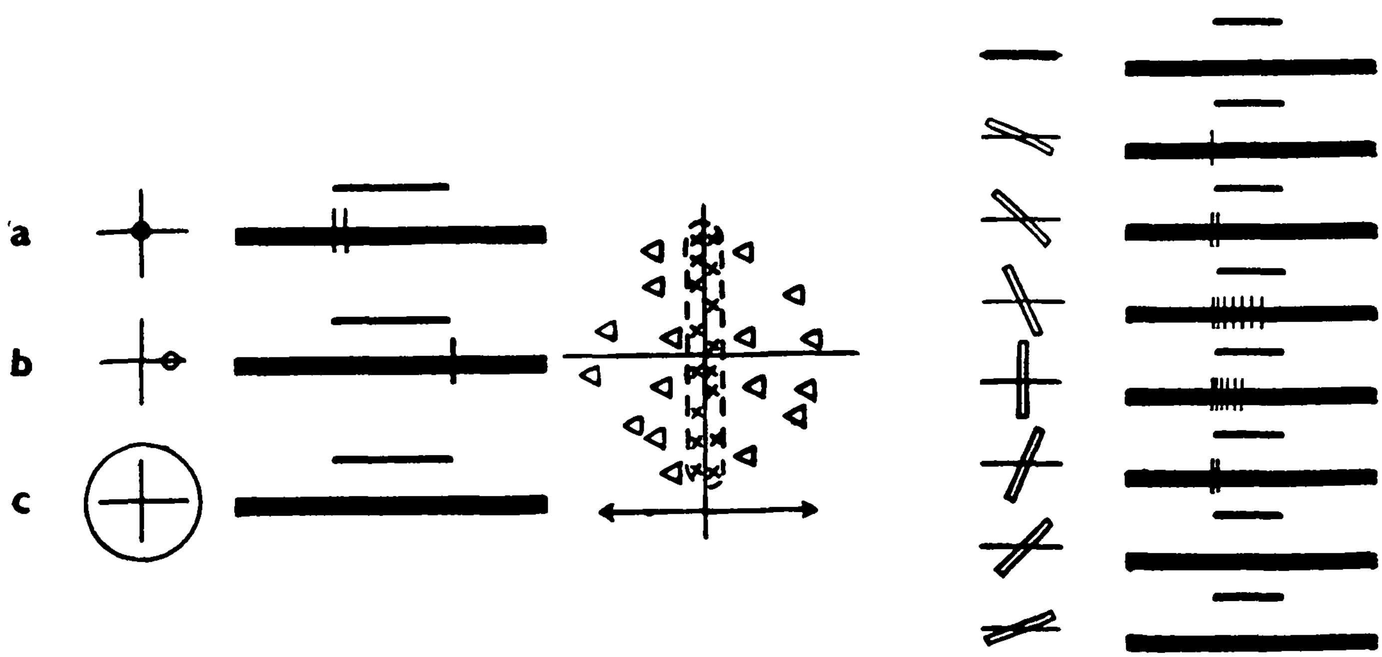

Fig. 6.—Responses from particular cells in the visual cortex of a cat

B

cells corresponding to the pattern displayed. On the right of Fig. 6 something even more remarkable is shown—the effect of various positions of an image on the output from a particular cell. This illustrates "recognition" of the vertical position.

It seems likely that these recognition processes are connected with the geometrical patterns exhibited by the dendritic fields of neurons in the cerebral cortex. Much recent theoretical work has revolved around constructing possible "models" for such a process. A key concept here is the idea of reinforcement. Suppose we have a network of logical devices connecting a set of inputs to an output. Suppose further that we wish to "teach" this network how to "recognize" certain patterns in the input data. And suppose we have a means of "rewarding" the network every time it correctly recognizes one of the certain patterns, this reward having the effect of reinforcing all those paths through the network which lead to the successful recognition. Similarly punishment for wrong recognition would lead to a diminution of the pathways responsible. Then such a system might be capable of being taught to recognize patterns, and might thus provide a basis for understanding the pattern recognition processes of the visual cortex.

Fig. 7 shows one such model devised by Dr. W. K. Taylor of University College, London. The inputs to the model come from nine visual receptors (photocells) arranged in a 3 × 3 matrix. Patterns are centred automatically by combining the outputs of the detail filter, whose output is fed via these intermediate units to a maximum amplitude filter which determines the pattern identification. The system is "conditioned" or "trained" by successive operation of the reward and punishment switches S1 and S2.

The operation of such models has not, of course, been verified. Their purpose has been mainly to stimulate biological thinking with insight derived from computer technology.

Software

So much for hardware. What about software? Here again there are many stimulating analogies. At the lowest level there are bootstrap routines—built-in programs provided by the genetic machinery to give the animal its instinctive communication with its mother. Then there are the symbolic assembly languages or baby talk, and finally the high-level languages.

Recently computer software has also, of course, come to include supervisory and executive programs for controlling computing systems as a whole, and this is an exceedingly highly developed aspect of brain software, closely linked to its total organization.

Recently Professor Paterson at Strathclyde has been formulating a model of this organization which brings out clearly the manner in which the brain delegates authority to its various parts, very much in the way in which a company is organized. Indeed, the boot may

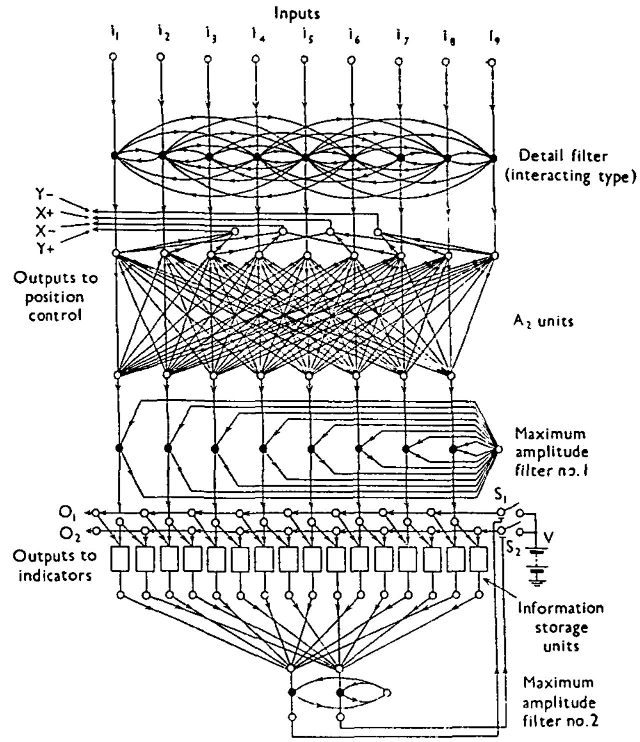

Fig. 7.—Automatic pattern recognition apparatus devised by Dr. W. K. Taylor

well be on the other foot inasmuch as the brain itself may well be the pattern on which viable human organizations have to be built.

There are many ways in which a model of this sort can be used to interpret the broader features of human behaviour in clinical terms. In **Fig. 8,** for example, cutting the topmost link on the left has the effect of severing the managing director from his planning staff and creating a schizophrenic organization.

Such organizational models as this which look at the brain in broad terms bear the same relation to the details of neuronal organization, as for example, do models of the economy as a whole bear to our domestic budgets, and there are even greater difficulties in forging links between the macro and micro models. However, these broader models of human behaviour are also of great interest and have in some cases been extended to cover the reactions of groups of people. Take the model illustrated in **Table 1**—formulated by Professor Simon of the Graduate School of Industrial Administration of the Carnegie Institute of Technology. Here we have a representation of the dynamics of the behaviour of a group of people, where as you see the letter I represents the interaction of the members of the group, F the level of friendliness within the group, A the amount of activity within the group, and E the amount of externally imposed activity. Such a model is in quantitative agreement with a number of observations. Equation (1) shows that the degree of interaction between members of a group depends on the level of friendliness and the activity level of the group. The inherent level of

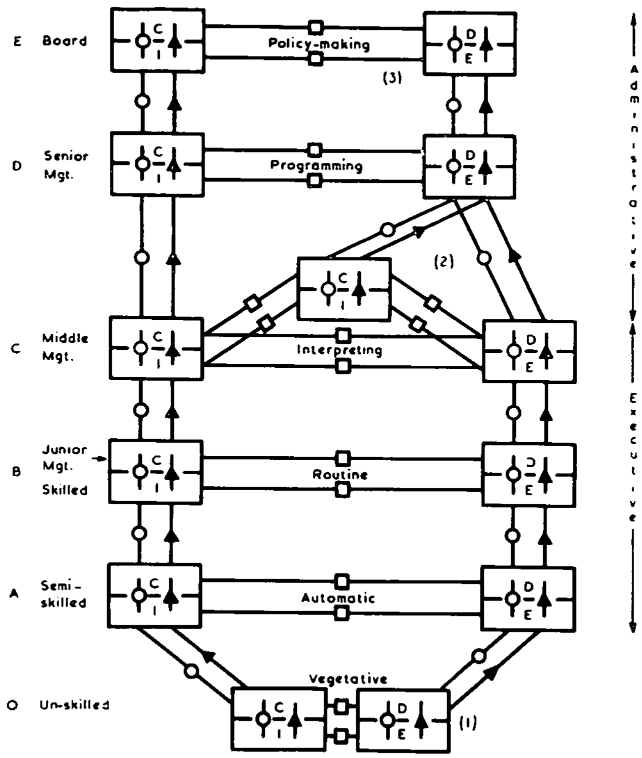

Fig. 8.—Organizational model of brain illustrating the similarities to the administrative structure of a company

friendliness is set by the coefficient β in equation (3) which is called the "congeniality coefficient". Using this principle much more elaborate models could be constructed, and these might be of great value in predicting how groups of people may interact and how companies should be controlled.

Table 1

Representation of dynamics of group behaviour

$I(t)$	Interaction among members
$F(t)$	Level of friendliness
$A(t)$	Activity of group
$E(t)$	Externally imposed activity

$$I(t) = a_1F(t) + a_2A(t) \quad (1)$$

$$\frac{dA(t)}{dt} = c_1[F(t) - \gamma A(t)] + c_2[E(t) - A(t)] \quad (2)$$

$$\frac{dF(t)}{dt} = b[I(t) - \beta F(t)] \quad (3)$$

Thus most situations that can be described accurately enough in words to make a logical decision on subsequent action can of course be described by a series of simultaneous equations. All of us are constantly solving our own versions of such sets of equations "in our heads". Generally, though, we can never get beyond solving a situation needing at least seven equations to describe it. A computer can of course do very much better than this—if only the information can be given to it. Work on this is bound to be undertaken on an increasing scale, for the results of such calculations could be of really fundamental importance.

The schism between the arts and the sciences has been a real one. The possibilities of a better understanding of ourselves can be a basis not only for the co-ordination of many scientific disciplines, but the co-operation also between the arts and the sciences. Surely now there is a chance of greater understanding bringing more than the purely material benefits that science has yielded so far.

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